TREE SPECIFIC GRAVITY
OF ENGELMANN SPRUCE
FROM COLORADO AND WYOMING

COLORADO STATE UNIVERSITY

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ABSTRACT OF THESIS

TREE SPECIFIC GRAVITY OF ENGELMANN SPRUCE FROM COLORADO AND WYOMING

Wood specimens were collected from 316 trees sampled from 13 national forests in Colorado and Wyoming. The specimens included 1720 cross-sections taken at various height levels and 316 breast height increment cores.

Specific gravity measurements were made on each specimen based on the ovendry weight and green volume. A weighted whole-tree specific gravity value was computed for each tree and specific gravity variations within and between trees were studied. Equations were developed for predicting whole-tree specific gravity from increment core specific gravity and other easily measured characteristics.

The computed whole-tree specific gravity for the species, based on these data, is 0.334. This value represents an improvement of 0.014 over the presently accepted value. The mean specific gravity of the increment cores is 0.342 which is significantly different from that of the whole-tree. The mean specific gravity of the breast height cross-sections, however, is not significantly different. Using the multiple linear regression technique, four of the variables tested; core specific gravity, rings per inch, topographic site and elevation significantly affect whole-tree specific gravity accounting for 60.13

percent of the variation. Core specific gravity, however, accounted for 57.19 percent of this variation. In a limited study of 21 trees, the increment cores were segmented in one inch lengths and each segment weighted by the respective cross-sectional area each represented. This procedure improved the correlation between the core and tree specific gravity by 16.36 percent for the 21 trees.

In the vertical direction, specific gravity was found to be highest at the base of the tree, decreases for the first 25 feet at which point it steadily increases for the next forty feet. Above the 75 foot level specific gravity tends to decrease once again. In the transverse direction, specific gravity was found highest in the area of the pith and decreases outward. While specific gravity was found to decrease with increased tree diameter there occurred a slight increase with increasing age. Higher specific gravity values are associated with a rapid rate of growth. Specific gravity tends to decrease at a rate of 0.008 per 1000 feet rise in elevation and increases at a rate of 0.003 per degree increase in latitude. Extractives were found to contribute approximately three percent to the specific gravity of Engelmann Spruce wood.

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CHAPTER I

INTRODUCTION

Research encompassing the specific gravity or density[1] of wood has been emphatically pursued in the United States over the past 35 years. Interest in this wood property was reported in Europe as early as 1848. In the United States research has been in the pursuit of basic data by species, the variation within - and between - trees plus methods and techniques of measurement.

The specific gravity of wood cell wall substance averages 1.53[2] (80). This is quite constant for all tree species. In contrast, the bulk specific gravity of a wood varies considerably between species and to some extent within a species[3]. Bulk specific gravity includes

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[1] Throughout this study wood density and specific gravity will be used interchangeably. In the United States, the specific gravity of wood is the ratio of ovendry weight to the weight of an equal volume of water at the same temperature; the volume being computed in the green or swollen condition.

[2] This value is believed high due in part, to the compressibility of the displacement media (water) used. A more realistic value of 1.46 was believed achieved by using helium gas. (81). However, more recent research indicates that this value is low since some cell wall voids are inaccessible even with helium (92).

[3] Throughout this thesis, bulk specific gravity will be implied.

in its measurement the wood substance, void spaces, extraneous elements and water. Most of the commercially important woods in the United States have specific gravity values ranging between 0.3 and 0.8. Specific gravity of clear extractive free wood, is recognized as the single most satisfactory indicator of wood quality.

Many of the strength properties of wood are directly or closely correlated to specific gravity. Generally, end-wise compressive strength and stiffness,[4] vary directly with specific gravity (90). Bending strength or fiber stress at proportional limit and modulus of rupture in static bending, increase slightly more than an equal specific gravity increase. Toughness or shock-resistancy varies almost as the square of specific gravity. Therefore, a piece of wood having twice the density of a second would be expected to have double the stiffness and endwise crushing strength, about $2\frac{1}{2}$ times the bending strength, and approximately $3\frac{1}{2}$ times the toughness as the second (90).

Properties other than strength are also affected by wood specific gravity. Dimensional stability, treatability, paint holding capacity, glueability, thermal conductivity, dielectric properties and nail withdrawal resistance are all influenced by specific gravity. Generally, high specific gravity is associated with improved properties. For

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[4] Compressive strength measured by maximum crushing strength and fiber stress at proportional limit in compression parallel to grain. Stiffness as measured by modulus of elasticity in compression and in static and impact bending.

some properties however, wood of low specific gravity is preferred. Less dense wood is more dimensionally stable, holds paint better, is more workable and smoother textured than heavier wood. All of the properties improved with increased density can be attributed to the increase in wood substance. Accurate specific gravity data and rapid field methods of determining this property, can assist in attempts to scale logs by weight. Pulp yields are also directly correlated with specific gravity. A ten percent variation in raw material specific gravity would yield a four percent change in pulping costs (19).

Englemann spruce (Picea engelmannii Parry) is rapidly becoming more commercially important. In 1962, about one-half of Colorado's saw log cut was Englemann spruce, while the five years prior to 1962 produced an 11 percent increase in lumber production (52). The species natural range extends from Southern Arizona, north to Central British Columbia, and from the Cascade range of Oregon and Washington, east to Central Colorado. The tree attains heights of 100 to 120 feet with corresponding breast height diameters of 18-30 inches. A light colored wood is produced which is light weight, even textured and usually straight-grained without any characteristic odor or taste. The wood is easily worked, glues well, has average paint-holding ability, has little tendency to split, is low in ability to hold nails, shrinks moderately and is easily dried. Major uses are pulpwood, cooperage, boxes and crates, general building purposes, boat building

and plywood. Promising research is underway at Colorado State University in its use for particleboard.

Nearly 50 percent (39 billion board feet) of the Engelmann spruce sawtimber volume in the United States is located in Colorado and Wyoming. Due to the increased use and interest in this species as a raw-material, research has been and is underway at Colorado State University (8), private industry (77), and at the United States Forest Products Laboratory.

The published specific gravity values for the species are 0.32 at 80 percent moisture and 0.34 at 12 percent (99). These values were established from specimens collected from ten trees cut from two Colorado counties (46). Subsequent research has suggested that the specific gravity of Engelmann spruce wood is somewhat higher than the reported value. Bodig and Troxell (8) indicate a somewhat higher value from specimens cut from stress-graded dimension lumber. A study at Potlatch Forests, Inc., revealed a value of 0.35 based on 114 trim ends collected at regular intervals during a sawmill cut of 111,554 boardfeet of logs (77). In a study in Canada, Kennedy (39) reported a specific gravity value of 0.38 for the species. Because of the differences reported in the limited studies, the primary objective of this study is to determine the whole-tree specific gravity of Engelmann spruce wood based on a large and representative sample of trees from Colorado and Wyoming. To achieve this objective, 316 trees were

sampled destructively in 13 National Forests. The trees were taken from 92 cutting plots and 47 geographic locations. Secondary objectives developed as follows:

1. To develop a regression correlation relationship between whole-tree specific gravity and increment core specific gravity.

2. To determine specific gravity isopleths for different tree heights and at a given height.

3. To analyze the effect of geographic range, age and location on specific gravity.

The statistical population to which this study applies can be defined as; all the living merchantable Engelmann spruce trees, of average form, good vigor, without decay, excessive branchiness, or lean, between 5.0 and 30.9 inches diameter breast height growing in Colorado and Wyoming.

CHAPTER II

REVIEW OF LITERATURE

There are a number of causes for specific gravity differences between trees as well as within trees. Specific gravity differences between trees are caused by enrivonmental factors, properties of the stand, soil conditions and, to a lesser extent, the geographic location. Within a given tree, differences in specific gravity are related to the proportion of springwood to summerwood, moisture content, percentage of extractives, reaction wood, decay and the proportion of cell wall substance per unit of volume. These within tree properties vary with position along the length of the bole as well as in the transverse direction. Other variations are due to age, growth rate, and diameter. Because of these many properties and factors causing variation in specific gravity, considerable interaction results between variables making difficult a precise evaluation of the effect of one individual property or factor. A number of papers have been published in pursuit of the causes of specific gravity variation. Other research has been directed towards the techniques and methods of measuring specific gravity of wood along with the prediction of a tree's specific gravity by utilizing several easily measured properties.

Three reports published in recent years include comprehensive reviews of literature; Collett, (14) Goggans (27), and Larson (42). In 1965, a symposium was held at the Forest Products Laboratory, Madison, Wisconsin, for the purpose of discussing wood density as associated with wood quality. The symposium assembled persons of varied backgrounds and interest in wood density or specific gravity. The participants discussed the importance of specific gravity in predicting wood quality from the aspect of several end-use products. The proceedings (19), include a paper presented on the progress of wood density research at schools as well as a progress report on research relating specific gravity to strength.

Methods for measuring wood specific gravity

The specific gravity of wood is simply its ovendry weight divided by the weight of an equal volume of water. In the United States, it is customary to use the volume of wood in the saturated condition or when green. The greatest problem with measuring wood specific gravity is in arriving at the volume of the specimen.

A number of methods have been devised for determining specimen volume. For specimens highly regular in shape, the volume may be determined by direct measurement of dimensions. For a high degree of accuracy, the method is limited by the tedious work required to prepare the specimens. For irregularly shaped specimens, the volume can be determined by the water or mercury immersion method.

Both methods are based on Archimedes principle, that an object when held submerged is buoyed up by a force equal to the weight of liquid displaced. This force can be measured directly by determining the resistance when the object is held submerged in the liquid, or by measuring the amount of liquid displaced. When water is used, the specimen must be in the saturated condition or coated with paraffin wax to prevent the absorption of water. Mercury can be used for specimens at any moisture content, provided the pores or voids are not large enough to entrap the dense liquid. Coating can result in erroneous volume measurements. The volume of increment core samples can be determined by calibrating the borer used plus measuring the length of the specimen. All of these methods are considered as standard. The procedure for their use, is published by the American Society for Testing and Materials (3). Two rather rapid and practical methods were reported by Paul (61) and Paul and Baudendistel (64). These methods lack the accuracy usually needed in the laboratory but serve adequately in the field. In 1954 Smith (71) introduced the maximum moisture method which involved measuring the specimens ovendry weight and weight when completely saturated with water. Prior to Smith's work, the method was used by Keylwerth. In a subsequent paper, Smith (72) compared the maximum moisture method with the water immersion method, and showed an average difference of less than one percent of the mean water immersion specific gravity.

An improved method for rapidly determining specimen volume was reported by Heinrichs (37) in 1954. The method is again based on the buoyancy principle or water immersion method. A Toledo balance is uniquely adapted to measure a specimen's tendency to sink or float. This method is perhaps the most practical way of measuring large irregularly shaped specimens for large scale studies. Smith (74) also adapted this method to the measurement of the volume of green wood chips.

Still other methods have been devised for measuring specific gravity. The photometric method used by Morschauser (55) is best suited for measurement of springwood and summerwood density. Klem (40) reports on the use of x-rays for determining the specific gravity of wood.

Predicting tree specific gravity with increment cores

Some silvicultural techniques are beneficial in improving wood quality. The response of wood specific gravity to thinning and pruning as well as genetic manipulations have been studied by a number of investigators. Such research can be greatly accelerated when sample trees need not be sampled destructively to evaluate specific gravity response to treatment. The use of increment cores to predict tree specific gravity is unique in that destructive sampling is not necessary. If core specific gravity adequately predicts whole-tree specific gravity,

then large scale studies of a species can be conducted for a fraction of the cost required to collect larger specimens.

One of the first investigations initiating the use of increment cores was by Markwardt and Paul (47) in 1946. The specific gravity of increment cores and blocks was compared statistically. Although the specific gravity of the cores was generally lower, they reported no significant difference between the two methods. In subsequent research, Spurr and Hsiung (78) compared the specific gravity of cores and blocks taken at three height levels from each of 14 trees. The core values were significantly lower but the standard error of the difference was only 0.003 indicating a good correlation.

During the past ten years, work has accelerated in the use of increment core sampling. Mitchell (53) reported on the techniques and equipment used in field sampling and reviewed methods and equipment used in the laboratory to determine specific gravity as well as other properties from increment cores. Following this publication, Wahlgren and Fassnacht (88) reported the results of sampling 100 trees of four southern pine species. The average whole-tree specific gravity of the trees was determined from cross-sectional disks and compared with cores extracted at breast height. A significant relationship was noted. In a study of loblolly pine, Zobel, et al. (104) reported that specific gravity and cellulose yields at breast height are good indicators of the whole-tree properties. They indicated, however, that for

older trees, the use of outerwood properties at breast height compared to the outerwood properties of the whole-tree held the best relationship. While studying several properties associated with specific gravity of southern pine grown in southern Illinois, Gilmore, et al. (24) found that the product of the core specific gravities taken at the one foot level and at breast height provided a better relationship with whole-tree specific gravity than breast height core specific gravity alone. While studying pulp properties, Einspahr, et al. (22) reported satisfactory estimates of percent lignin, percent summerwood, percent extractives, percent juvenile wood and specific gravity for the whole-tree can be made using increment cores. Barefoot, et al. (6) reported that cores over-estimated specific gravity in four selected loblolly pine trees. In a multiple regression analysis, Christopher and Wahlgren (12) using core specific gravity and other variables, reported that the best independent variables for predicting tree specific gravity were disk specific gravity, age divided by diameter breast height and the reciprocal of merchantible length of bole.

Some of the work reported above has led to the initiation of comprehensive studies using increment cores. The first such investigation was the Southern Wood Density Survey (76) where cores were collected from 15,786 trees in seven Southern States. To determine the whole-tree specific gravity for comparing with the specific gravity of cores, cross-sectional disks were taken at five foot intervals from breast

height to a three inch diameter top. With this data, regression equations were developed in four southern pine species. The Western Wood Density Survey (97) followed, with the collection of 30,326 increment cores from 9 Western species. Regression equations were then developed for these species.

In the most recent investigations, Baker (4, 5) and Maeglin (45), used increment cores to study specific gravity relationships in red pine. Pronin (66) reported cores over-estimated the specific gravity of logs. Wahlgren et al. (89) found that the use of two increment cores was an improvement over single core sampling for seven of eight species investigated. In a study of loblolly pine after thinning, Smith (75) used cores to study the before-and after-effect on tree specific gravity and growth ring characteristics.

The influence of environmental factors and geographic range on specific gravity

The surrounding conditions that influence the growth of trees have been investigated in attempts to explain specific gravity differences. Some of the first interest was shown by Hartig (36) who associated favorable growing conditions with wood of maximum strength and weight. Paul (59), while stressing the importance of stocking density, also concluded that environmental conditions are very important in determining wood quality. Such a factor as moisture deficiency causes slow growth and results in less summerwood production and a

decrease in the specific gravity of the wood. Myer (56) reported that such factors as slope direction, elevation and soil conditions varies so greatly that little correlation exists with specific gravity. Several studies, (32, 34, 44, 50, 58, 102 and 103) reported little to no relationship with specific gravity and site factors studied. Spurr and Hsiung (78) suggested that some of these negative findings are not adequately supported statistically and from their study concluded the major differences in site quality may produce variations in specific gravity associated with summerwood production. In a study of loblolly pine (25), 49 percent of the variation in specific gravity was accounted for by environmental factors and percent latewood.

Considering moisture alone, Zahner, et al. (101), subjected six red pine trees to controlled soil moisture conditions. They found 100 percent more xylem cells formed in the lower boles of irrigated trees, however, the percentage of latewood was equal in both the irrigated and unirrigated trees at comparable stem positions. Supporting these findings Taras, (84) reported little relationship between the specific gravity of earlywood and latewood with rainfall while specific gravity had only a slight positive relationship with rainfall. In contrast, Goddard and Strickland, (26) found that available moisture influenced summerwood formation and hense specific gravity. One should note, however, that comparison of rainfall and available moisture has little meaning without considering the water holding properties of soils. In

a most recent publication, Smith (75) reported more abundant rainfall reflects a decrease in the size of earlywood cells and an increasein summerwood cell size for loblolly pine.

As with environmental factors, investigators studying the effect of geographic location on specific gravity have reported conflicting results. Several researchers (28, 32, 46, 56 and 82) have concluded that the variation caused by local phenomena are so great in magnitude that little differences can be associated with range or latitude and longitude differences. As one would expect, there appears to be a strong interaction between geographic location and environmental factors. In work leading to the Southern Wood Density Survey (54, 98), it was found for Mississippi pines, specific gravity decreased diagonally across the state from southeast to northwest. This trend was attributed to differences in rainfall resulting from warm prevailing winds from the southease rather than to latitude alone. Similar trends were reported for loblolly pine in southern Illinois (25). Goddard and Strickland (26) report generally the same in their study of slash pine. Echols (21) found a high correlation between latitude and density in scotch pine while Born (10) indicated wood density may be higher in the western part of Alaska while studying the specific gravity variation of Alaskan trees. In contrast, Harris (35) investigating Monterey pine density in New Zealand, found the highest density in the Northern part of its range. He suggests the increase is primarily due to differences in soil properties. Still others, (49, 50), found little or no relationship between specific gravity and range. One species showing a

substantiated difference between geographic locations in Douglas-fir. Drow (20) found that Rocky Mountain Douglas-fir had a smaller percentage of summerwood than the coastal type of any growth rate. But here again, the difference is not believed due to differences in range alone but that two separate populations are involved.

Stand, site and silvicultural considerations

To further complicate specific gravity variations caused by environmental factors and geographic range, one must consider stand characteristics and silvicultural affects. Paul (62), reported lower specific gravity resulting from fully stocked second growth Douglas-fir stands on good sites than on poorer sites. Many investigators found site poorly correlated with specific gravity differences (7, 34, 44, 70, 78 and 93). Jayne (38), however, reported site influenced wood density for plantation-grown red pine.

Stand density or stocking level is considered to influence specific gravity in three studies (62, 65 and 78). Hamilton and Matthews (33), found a higher percentage of latewood and thus, increased specific gravity in dense stands. Similarly, Paul (62), concluded that trees from open stands produce greater amounts of springwood than summerwood, while their proportions were nearly equal in dense stands. In other research where multiple regression techniques were used, basal area per acre (an indicator of stand density), was entered as a predictor of specific gravity. Using this variable, Wheeler and

Mitchell (98), found a weak correlation between specific gravity and basal area, while Maeglin (45), found no relationship between basal area and specific gravity. In the latter case, the simple coefficient of determination (basal area with tree specific gravity) was only 0.0644.

In studying the affects of controlled stand density through thinning, Boggess, et al. (9) reported thinning to be less and less advantageous as site quality increased. More recently, Smith (75), found that thinning and pruning loblolly pine at age nine years, resulted in wood of higher density than that from unthinned stands. When thinnings were delayed until the twelfth year, light thinning resulted in a significant specific gravity increase over the earlier thinning. This supports Mart's (48) conclusion that pruning has the effect of reducing springwood formation, however, he believed this to be due to the depletion of reserves rather than the thinning.

Another assumption that has gained substance is that significant specific gravity variation can be accounted for by separating specimens into those from crown-formed and stem-formed wood (11). Wellwood and Jurazs (95), support this hypothesis in reporting a higher specific gravity in crown-formed wood than stem-formed wood in western red-cedar. This may add to the conclusion of another study (33), where specific gravity of loblolly pine was found to be higher in trees supporting large crowns. Wellwood (93), also reported a significant

difference in specific gravity of young Douglas-fir due to crown class, while Spurr and Hsiung (78) found absolutely no relationship in jack pine.

Genetics may also play an active role in causing specific gravity differences. One objective in mass increment core sampling has been to identify "plus trees" with respect to high quality wood. Wheeler and Mitchell (98), implied that almost one-third of tree specific gravity variation may be due to genetic factors, while Zobel and Rhoades (103), have stressed the role genetic factors may play. In studies of clones (18), specific gravity and fiber lengths within clones were quite similar while differences occurred between clones. Positive relationships between specific gravity and genetic factors were also reported by Nylinder (58) and Maeglin (45).

Specific gravity variation with vertical position in tree

It is generally accepted that, for conifers, specific gravity tends to decrease with successive height levels. This is not a simple straight line relationship, but is compounded by slight deviations at periodic points up the stem. For the benefit of abridgement, the idiosyncrasies of each study will not be discussed here. Many papers (13, 15, 44, 45, 56, 60, 66, 78, 86 and 91) substantiate the general trend of decreasing specific gravity with increasing height level for conifers. Reasonable explanation for this behavior has been offered by Myer (56) and Turnbull (86). Myer suggested that wood in the lower bole of trees

is finer textured, resulting in more wood substance and consequently a higher specific gravity than that found in the wood from the upper bole. Turnbull explained that the aggregate specific gravity in pine receded with increased tree height due to a gradual tapering of the summerwood sheath in ascent up the stem.

A few researchers report little differences in specific gravity are associated with the woods vertical location in the stem. Wellwood (93), found the trend to be irregular. Cooper (16), after removing the differences due to stem-and crown-formed wood, found little correlation between specific gravity and height in red pine. Likewise, Jayne (38) noted no particular trend.

A reverse trend has been observed by Grigal and Sucoff (84), for red pine and by Wellwood and Jurazs (95), for western redcedar. Spruce, as well, seems to defy the conventional relationship as reported by Hakkila (30), Hale and Fensom (31), and Nylinder (57). In lodgepole pine, Collett (14), found specific gravity to decrease rapidly in the first 10 feet of bole length, remain somewhat constant up to 50 feet, and then increase once again. Similarly, Krahmer (41), reported specific gravity highest at the stump level in western hemlock, decreases considerably at the 8 foot level with a trend towards decreasing specific gravity with additional height.

Other investigators offer explanations for specific gravity differences between height levels. Richardson (68), concluded that within

one annual ring traced down-ward from the apex of the tree, the density pattern first of all decreased to a minimum at about the fifth internode from the apex and then increased to the twentieth. No apparent variation was reported beyond the twentieth internode. Stage (79) concluded that factors such as crown development and vigor may affect the specific gravity in wood from the upper portions by supplying additional auxins from elongating laterals. Some of the variation in breast height specific gravity may be due to the different sampling distances from the apex of the trees. In discussing the same subject, Wellwood and Smith (96) indicated that density is influenced by the distance the wood is located from the base of the live crown at the time of annual increment formation, since at this point, auxin supplies are at a maximum. This results in an abundance of springwood cells and a lower specific gravity. Wahlgren, et al. (89), reported that a possible explanation for the behavior of spruce is that the trees lack a pronounced decrease in latewood percentage with tree height and low specific gravity of the latewood itself. Also, there exists significantly higher specific gravity of the earlywood in the juvenile core as compared to mature wood.

Considering total tree height alone, Maeglin (45) reported that a regression of total height with 180 degree core specific gravities produced the best regression equation for predicting specific gravity in a plantation survey. In the Western Wood Density Survey (97),

however, total tree height did not prove too valuable in predicting specific gravity.

Specific gravity variation due to age, growth rate and horizontal position in the tree

Age, growth rate and horizontal position in the tree are considered together because of the extreme interaction among the variables. Because of this interaction it becomes difficult to view the effect of any one variable independently. With this in mind, the variables as discussed below should be viewed along with their relationship to one another. Many studies included but one of the three.

Of the literature reviewed, five papers (16, 45, 70, 102 and 103) concluded little to no relationship exists between specific gravity and age. Cooper (16) arrived at his conclusion, however, after removing the variation between crown and stem formed wood. Of those reporting an increase in specific gravity with age were Rendle and Phillips (67). They reported that wood formed later in life is invariably denser than that formed earlier at the same rate of growth. From the Western Wood Density Survey (97), it was concluded that specific gravity increased with age. They found that when cores were separated according to age, ring width significantly influenced specific gravity during the first decade of wood formation, while tree age has the greatest influence in later life. McElwee and Zobel (49) reported a small but significant correlation between mature specific gravity and age.

Yandle (100) concluded that there apparently is some factor related to age, other than decreasing ring width, that influences the formation of the wood in such a way as to cause specific gravity to increase with increasing age. In a multiple regression analysis, Wahlgren et al. (89) found the function, diameter breast height divided by age, the most important variable when added to core specific gravity in predicting whole tree specific gravity. Similarly, Wheeler and Mitchell (98), reported that the reciprocal of age as the most important of nine variables for predicting core specific gravity. For the four species tested, this variable accounted for 63 to 81 percent of the total variation. In contrast, Wahlgren and Fassnacht (88) found age did not help when added to core specific gravity for predicting tree specific gravity. Of course, the effect of age may have been hidden in the whole-tree specific gravity variation accounted for by core specific gravity. Collett (14) also concluded that age was a significant variable in accounting for specific gravity variation but cautioned against generalization due to interaction with growth rate and other factors.

In looking at all the relationships of specific gravity and growth rate, the latter appears to be of little significance. Perhaps this is due to the fact that it is most difficult to remove the effects of all the variables that interact with it. Spurr and Hsiung (78) conclude that both height of the sample in the tree and the age of the wood must be held constant in any valid effort to isolate the effect of growth rate.

Further, if the position in the tree is held constant, there is little or no correlation between specific gravity and ring width. As with the other variables studied, a number of investigators report little or no correlation between specific gravity and growth rate (13, 35, 42, 58, 69, 73, 100 and 103). Turnbull (86) reported that growth rate is the principle cause for radial decrease in specific gravity when comparing trees of different age. He also found that wood of a given age has a fairly constant density regardless of growth rate. This conclusion is in conformance with that of Spurr and Hsiung discussed earlier as well as Luxford and Markwardt (44). Others report findings of a decrease in specific gravity associated with a decrease in growth rate or an increase in the number of rings per inch, (17, 23), while Jayne (38), Krahmer (41), Paul (63) and Wellwood (94), concluded a low specific gravity was associated with rapid growth. However, there must be consideration given to the species studied. It appears that both extremes in growth rate are undesirable. Growth rates conducive to the production of high quality wood are reported in references (1, 31, 44 and 56).

In discussing specific gravity variation in the transverse direction, the importance of other variables within a species and under a given set of conditions would directly affect the results as illustrated in the forgoing discussion. The standard behavior in conifers is for the lowest specific gravity to occur at the center or pith and gradually

but steadily increase towards the cambium. In older trees there tends to be a decrease in specific gravity at the outer extremes due to reduced growth and vigor. This general relationship has been found by several investigators, (14, 30, 58 and 100). Luxford and Markwardt (44) found in redwood that specific gravity decreased from the pith outward as did Krahmer (41) for western hemlock and Wellwood and Jurazs (95) studying western redcedar. Jayne (38) reported a high specific gravity adjacent to the pith in red pine, but once away from the pith no consistent trend was observed.

CHAPTER III

PROCEDURES

I. FIELD PROCEDURES

Sampling

Permanently established forest inventory plots were the basis for selecting wood density plots. From a listing of all forest inventory plots, established in spruce and spruce-fir timber types of Colorado and Wyoming national forests, wood density plots were proportionately selected using a table of random numbers. The forest inventory plots were selected initially by random pin points on aerial photographs. The number of wood density plots established in each forest was governed by the total spruce volume (small sawtimber and larger) existing in each forest as projected by inventory. Similarly, the number of trees cut in each diameter class was based on the timber volume in the various diameter classes. Two wood density plots were established approximately two chains apart in the vicinity of the forest inventory plots, i.e., within the same timber type as indicated by type maps. At each wood density plot, 2-5 trees were sampled destructively. A listing of wood density plots and sample trees by forest and diameter class is included in Appendix A.

Cutting plots

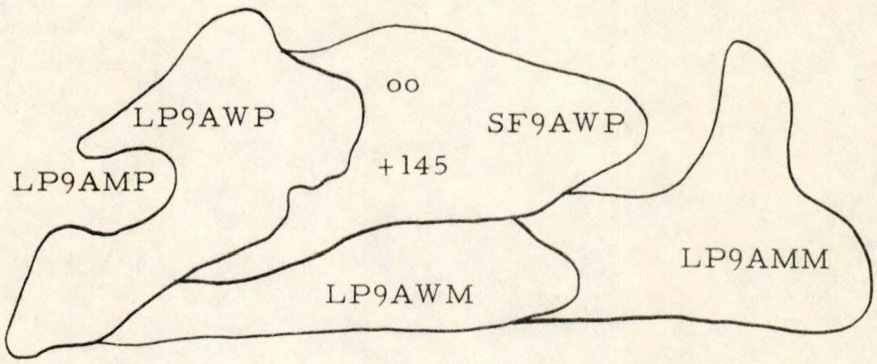
Initially, efforts were made to reference wood density plot centers to the forest inventory plot centers by chaining. Efforts to accomplish this objective resulted in the expenditure of an unreasonable amount of field time. A decision was made that it would be sufficient to assure that the wood density plots be established in the same timber type as that in which the forest inventory plot existed. U.S. Forest Service timber type maps simplified realization of this objective, (figure 1). The basic criteria for wood density plot location within the timber type became its accessibility since the test specimens removed from each plot weighed from 150-200 pounds.

At each wood density plot the following data were collected:

1. State and county.
2. Longitude and latitude (to nearest minute).
3. Elevation (to nearest contour on topographic map).
4. Slope aspect (N, NE, E, SE, etc.).
5. Topographic site (steep slope, moderate slope, flat, etc.).
6. Stem count by species within a variable radius plot established with a wedge prism having a basal area factor of 9.325.

Once the first wood density plot was established, the sample trees cut and specimens and data collected, the identical procedure was used at the second density plot taken approximately two chains away in any cardinal direction that would place it in the same timber type.

Figure 1.--Typical plotting procedures using timber type maps.



+ = Forest inventory plot center.

o = Wood density plot center.

Sampling trees

Sample trees were of average form, good vigor and without decay, excessive branchiness or lean. Trees showing excessive pitch in the bole area and those without cones were not taken. Diameter requirements were within 5.0 -30.9 inches at breast height (4.5 feet).

Prior to felling, the breast height diameter was measured and recorded to the nearest 0.1 inch. The 4.5 foot point was marked on each tree. After felling the following data were recorded:

1. Total tree height (to nearest 0.5 foot).
2. Height to 5.0 inch diameter top (to nearest 0.5 foot).
3. Length of live crown (to nearest 0.5 foot).
4. Whether the tree was dominant or codominant.

The methods for collecting test specimens from each tree were similar to those outlined by Wahlgren and Fassnacht (88) and subsequently used by Pronin (64), Southern Wood Density Survey (76), Taras and Wahlgren (85) Wahlgren *et al.* (89) and the Western Wood Density Survey (97). Cross sectional specimens (1-2 inches thick in longitudinal direction) were taken at breast height and 10 foot intervals thereafter, until a 5.0 inch diameter top was reached. At each height level the cutting of specimens deviated as much as 8 inches to avoid the inclusion of branch wood. An increment core (0.212

inch diameter)[1] was extracted as near as practical to the breast height saw cut. Obtaining a core of normal wood extending from the outer bark to the pith was facilitated by having the tree felled with the cross-section exposed near the point of boring, (figure 2). The cores were stored in labeled drinking straws for future laboratory measurements, (figure 3). The cross sectional specimens were debarked when possible and labeled with plot number, tree number and position in the living tree, (figure 4). The specimens were placed in waxed string onion sacks which aided handling and storage while permitting the specimens to dry.

In addition to the cross sectional specimens and increment cores collected for this study, a 36-inch longitudinal section of the tree was taken from 89 randomly selected trees. This test bolt was labeled with plot number, tree number and position in living tree and returned to the Wood Utilization Laboratory at Colorado State University (figure 5). The test bolts were used to furnish mechanical properties test specimens for a separate study under the direction of Dr. Jozsef Bodig. This writer was responsible only for collecting the specimens.

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[1] Prior to the field phase, an increment borer was calibrated (I. D.) by taking 5 (five) increment cores from spruce wood and measuring each in one direction and at 90 degrees from this plane with a machinist's micrometer.

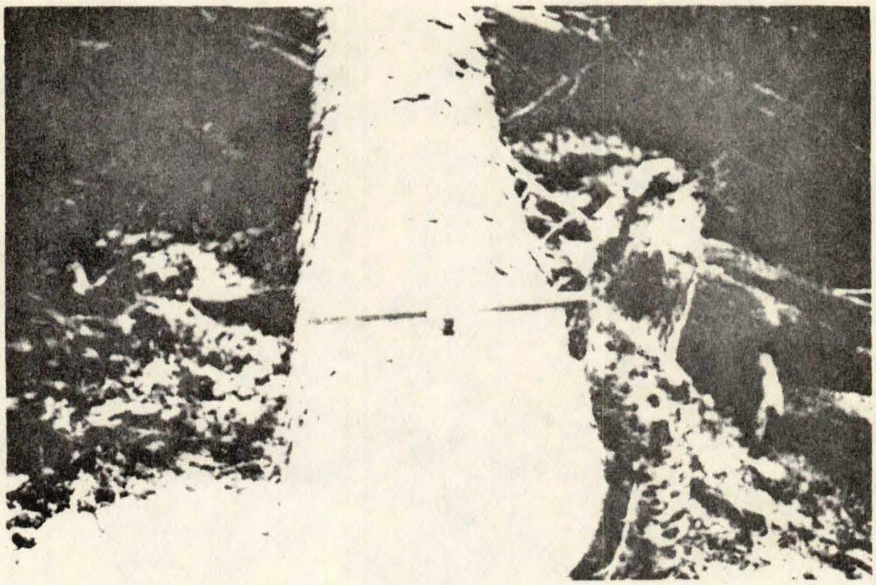

Figure 2. --Method of collecting increment cores once the sample tree was felled.

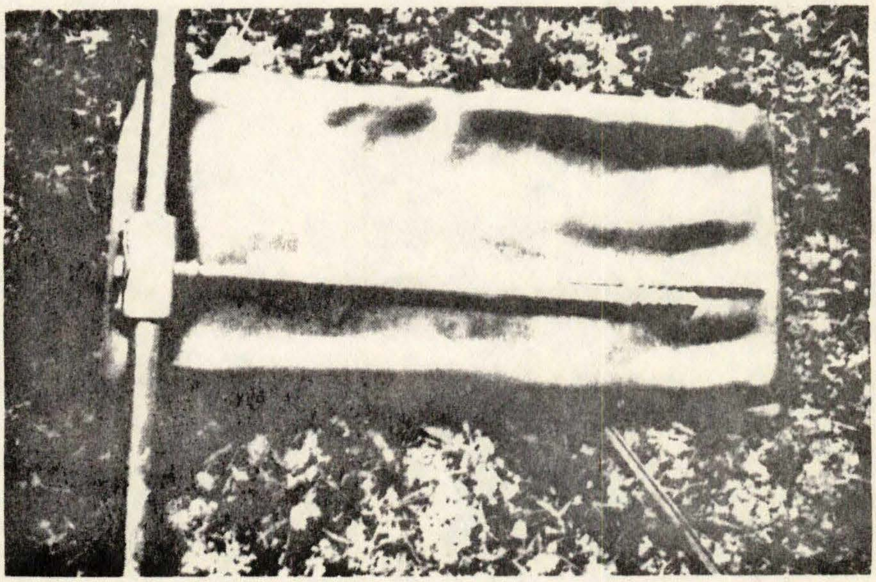

Figure 3. --Method of storing and handling increment cores.

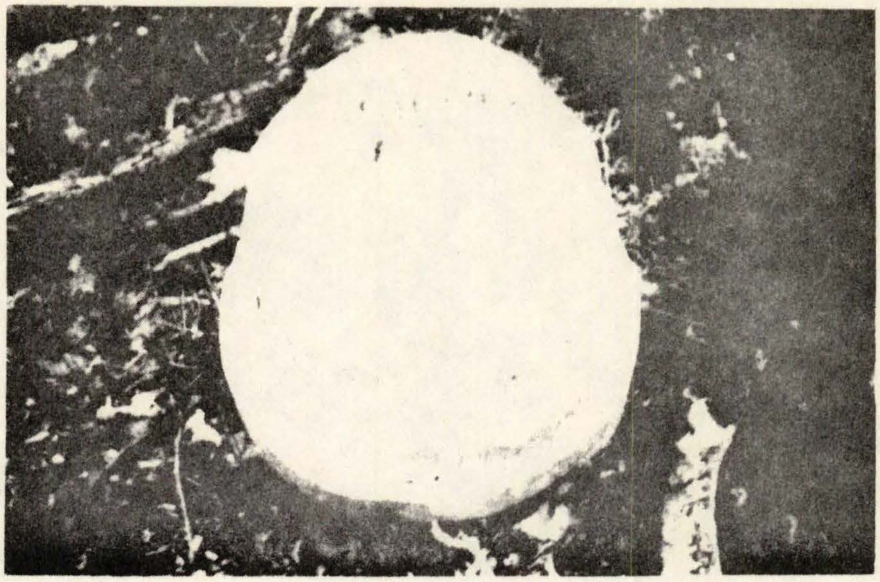

Figure 4. --A typical set of cross-sectional specimens from one sample tree.

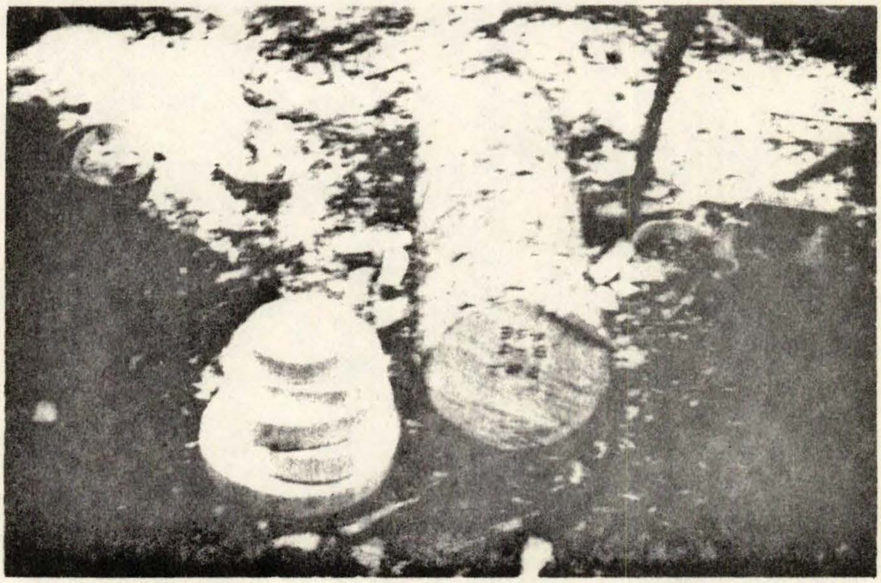

Figure 5. --A typical three foot longitudinal bolt from which strength specimens were to be cut for use in another study.

II. LABORATORY PROCEDURES

Increment core analysis

The cores were trimmed to exclude the pith and bark by using a core cutting block and scaple. Total tree age at breast height was determined by a growth ring count under a binocular microscope. The cores were placed in especially made racks and resaturated with distilled water under a vacuum for 48 hours (figure 6). Once saturated above the fiber saturation point, the cores were placed in metal drying trays and their length measured to the nearest 0.001 inch with a veneer caliper (figure 7). On the drying trays, the cores were dried to a constant weight at 105 degrees C in a forced air oven. After drying, the cores were individually taken from the oven and immediately weighed to the nearest 0.0001 gram on a pan loaded Mettler balance (figure 8).

Calculations

a. Saturated or Green Core Volume in Cubic Centimeters

$= (\text{bit radius in inches})^2 \; (\text{Length of core in inches})$

$\times$ conversion factor 16.387162 or

$= 0.5784646$ (core length in inches)

b. Core Specific Gravity = $\dfrac{\text{Ovendry Weight in grams}}{a}$

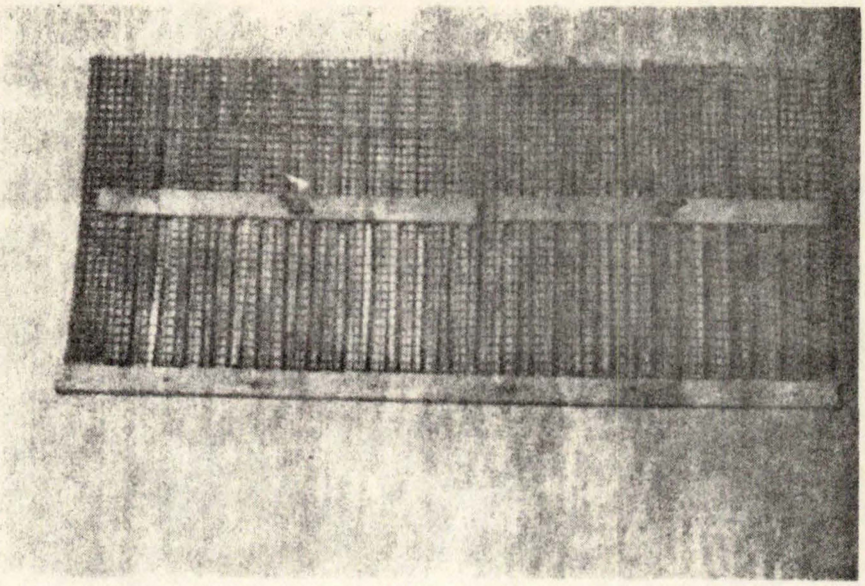

Figure 6. --Special rack for resaturating increment cores with distilled water.

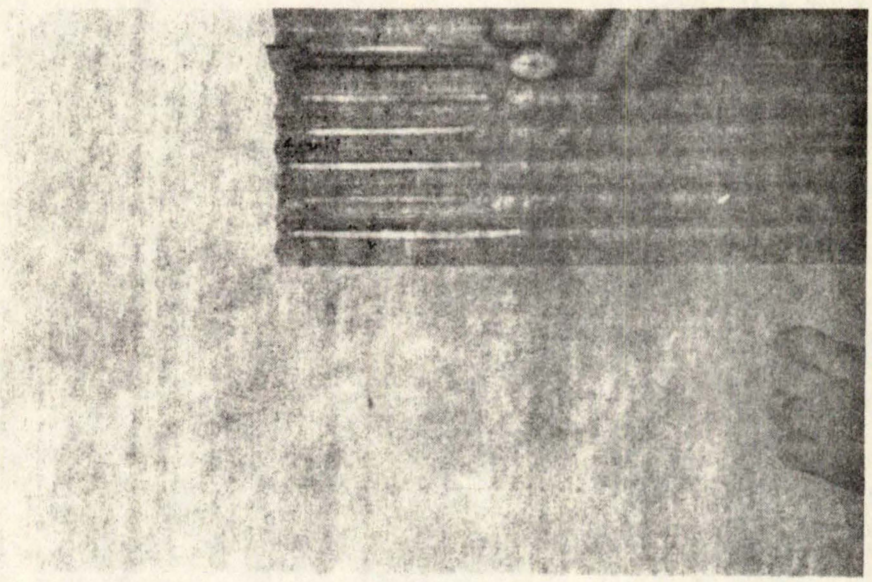

Figure 7. --Method of measuring increment core length with a veneer caliper while the core rested in a v-slotted drying tray.

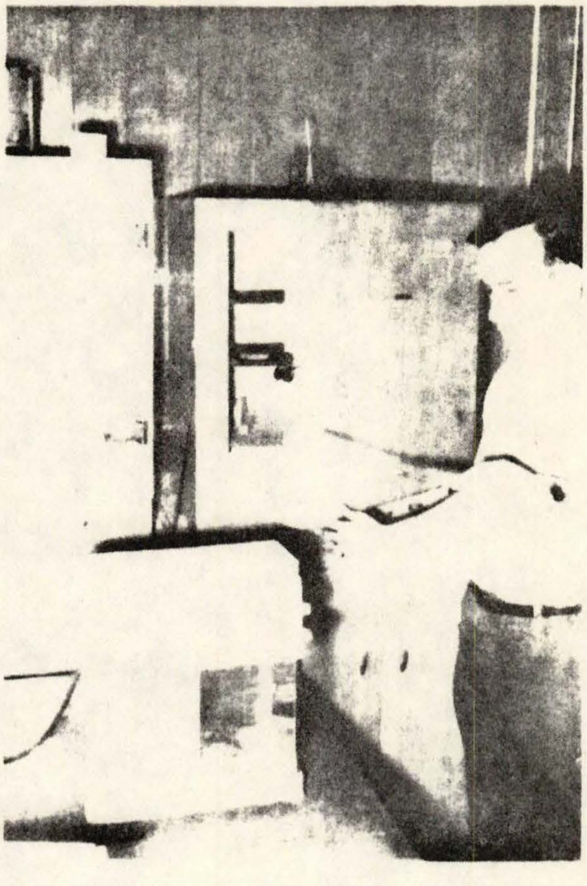

Figure 8. --Method of weighing increment cores immediately after removal from the forced air drying oven.

Cross-sectional specimen analysis

The laboratory procedure used in specimen preparation and subsequently determining their specific gravity was identical to that used by Collett (14) in a similar study on lodgepole pine but for one exception. Any attempt by this writer to present this procedure would be repetitious. Collett's description of this procedure is superbly set down with accompanying photographs.

The exception to Collett's procedure was the method used to ovendry the specimens. Due to the number and size of the Englemann spruce cross-sections, a more rapid method was used. The Wood Utilization Laboratory at Colorado State University is equipped with an experimental Standard dry kiln. This equipment facilitated the drying of 150-200 cross-sections at one time at 105 degrees C with constant air circulation and venting. The cross sections were loaded in the kiln to aid air circulation and the removal of randomly selected specimens, or parts thereof, for moisture content determinations (figure 9). After a drying period of 24 hours, six specimens were randomly selected and weighed to determine weight change due to moisture loss. This procedure was repeated every two hours until three successive weighings revealed no change in weight. The specimens were removed and weighed to the nearest gram on a top loading Mettler balance (figure 10).

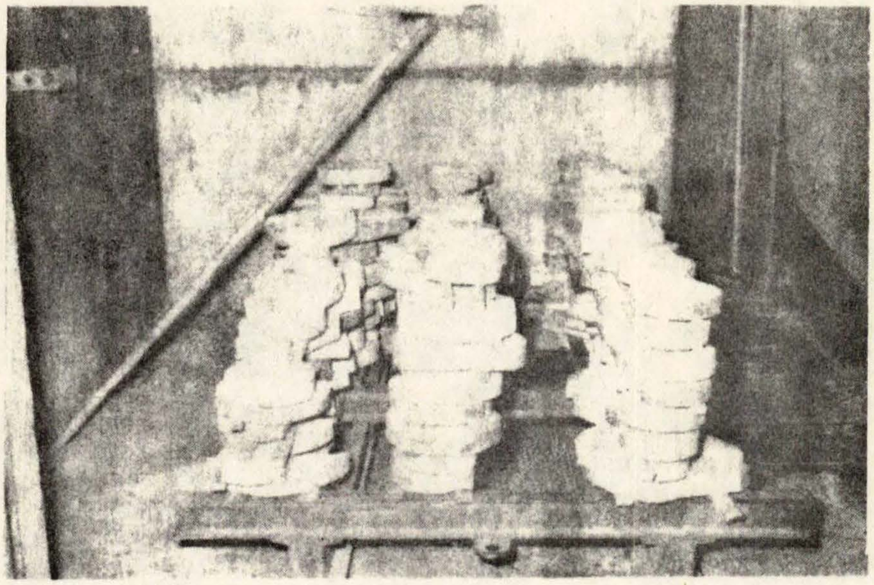

Figure 9.--Method of loading cross-sectional specimens on the dry kiln tram to facilitate air circulation and the selection of test specimens.

Figure 10.--Method of weighing the cross-sectional specimens as soon as possible after removal from the dry kiln.

Increment core weighting

Twenty-one increment cores were selected from trees having a diameter breast height of 12 ± 0.5 inches. The 12 inch diameter class was chosen by randomly selecting one of the 13 diameter classes. The cores were returned to the saturated or green condition with distilled water while under a vacuum. Once saturated, the cores were segmented into one inch zones from the cambium towards the pith. Each segment was measured in length to the nearest 0.001 inch with a veneer caliper. This measurement and the increment borer's inside diameter were used in computing the green volume of each segment. The segments were then dried at 105 degrees C in a forced air oven on labeled drying trays. The cores were placed on the labeled trays in the same order in which they were segmented. After determining the specific gravity of each of the 113 segments (based on green volume, ovendry weight), the mean of the outermost segments was weighted by the area represented in the outer one inch of a 12 inch diameter circle. This procedure was followed with the subsequent segments, i.e., the mean specific gravity of the second one inch segment from the cambium was weighted by the area represented in the outer one inch of an 11 inch diameter circle, etc.. Through this weighing, the outer segment represents 30.6 percent of the cross-sectional area while the inner inch represents 2.8 percent. In order to proportionately weight the segments the following equation was

developed: Weighted Core Specific Gravity =

$$\frac{(r_6^2-r_5^2)sg1+(r_5^2-r_4^2)sg2+(r_4^2-r_3^2)sg3+...+(r_2^2-r_1^2)sg5+(r_1^2)sg6}{r_6^2}$$

Where:

r_{1-6} = Radius of repsective circles of decreasing size from 6 to 1 inches.

sg 1-6 = Specific gravity of the respective segments from the cambium to the pith.

The effect of extractives on specific gravity

Thirty-five cubes, approximately 0.5 inch square, were collected from cross-sectional specimens chosen at random. Of the 35 cubes, 18 were taken from sapwood while 17 were taken from heartwood. The only destinction between sapwood and heartwood was made by taking the sapwood cubes immediately adjacent to the cambium and the heartwood cubes from the inner portion of the specimens. The specific gravity (based on green volume, ovendry weight) was determined for each cube by the water immersion method once the cubes were returned to the saturated condition with distilled water while under a vacuum. The ovendry cubes were then extracted in accordance with the A. S. T. M. standard D1105-56 for extractive free wood (3). The only exception to the procedure was that the extraction times were extended to 168 hours since the specification indicates ground wood should be used. The 168 hour extraction time was arrived at by periodically checking the residue in the distillation flask of the

Soxhlet extractor after removal of the solvent through distillation followed by evaporation. After extracting, the specific gravity of each cube was again measured.

To assure that all the water and alcohol soluble extractives had been removed from the cubes, the separated sapwood and heartwood cubes were ground in a Wiley mill to the consistency indicated in the A.S.T.M. standard. Since determining the specific gravity before and after extraction of the ground wood would require employing the pycnometric method, records were kept only to determine the weight loss during this second extraction. For greater protection against the loss of material, the ground wood was held in a Gooch-type crucible throughout the extraction.

CHAPTER IV

DESCRIPTION OF MEASUREMENTS

Aside from the initial calculations described in the preceding chapter, the bulk of the data analyses and statistical manipulations were conducted with the aid of an CDC-6400 computer. This equipment greatly reduced the time element in performing a step-wise multiple regression analysis which included many variables and the large number of observations.

Cross-sectional specimens

The three weights taken of each specimen were substituted in the following equation:

$$\text{Specific Gravity} = \frac{\text{ovendry weight}}{\text{Saturated weight in air} \pm \text{float or sink weight}}[1]$$

Whole-tree specific gravity

To express the specific gravity of a whole tree, the specific gravity of the cross-sectional specimens must be weighted with respect to the volume of wood each represents in the tree bole. The importance of this weighting is emphasized when specific gravity variation

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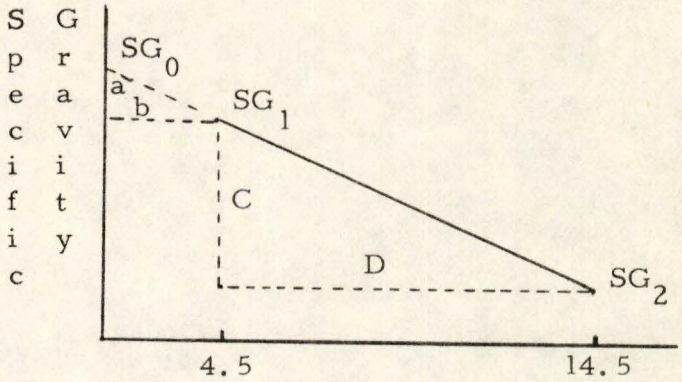
[1] The float or sink weight is that weight obtained with the specially designed Toledo balance. This adaption and its use are described by Heinrichs (37).

with tree height is considered. Since cross-sectional specimens were taken at 4.5 feet and at 10 foot intervals thereafter until a five inch diameter top was reached, the weighting between successive specimens was quite easily done. However, the weighting of the first 14.5 foot section was complicated as a result of not having a cross-sectional specimen at its large end or groundline. Consequently, an average of the diameters at the 4.5 foot level and at the 14.5 foot level would not result in the mean diameter of the first 14.5 foot log needed for computing its volume. Similarly, like averages of the specific gravities of these specimens would not produce the mean specific gravity of the first log.

For determining the mean diameter of the first 14.5 foot log, the percent diameter change from the 4.5 foot measurement to the 14.5 foot measurement was computed for each tree. The average change per foot was calculated which resulted in a constant percent reduction of the breast height measurement to arrive at the mean diameter of the first log or at 7.25 feet from the groundline. The volume of the subsequent logs was an easy calculation since diameter measurements were available from specimens cut at the extreme ends.

Similarly, the specific gravity value at the 4.5 foot level was extrapolated to the groundline. Again a straight line relationship was assumed between the specific gravity at 0.0, 4.5 and 14.5 feet. The

equation for extrapolating the specific gravity to the 0.0 foot level was developed as follows:



Height level in tree

By similar triangles,

$$\frac{a}{b} = \frac{C}{D}$$

Where: a= The specific gravity difference between that at the groundline (SG_0) and that at the 4.5 foot level (SG_1).

b= Distance between the above measurements or 4.5 feet.

C= The specific gravity difference between that at the 4.5 foot level (SG_1) and that measured at 14.5 foot (SG_2).

D= 10.0 feet.

Thus,

$$a = \frac{bC}{D}, \quad a = \frac{(4.5)\ (SG_1 - SG_2)}{10}, \quad a = 0.45(SG_1 - SG_2)$$

Then,

$$SG_0 = SG_1 + a \quad \text{or,}$$

$$SG_0 = SG_1 + o.45(SG_1 - SG_2)$$

The weighting formulas then become,

$$TTV = 0.079085(D_1 - D_1\ 0.03574)^2 + 0.013635(D_2+D_3)^2 + 0.013635$$

$$(D_3+D_4) + \ldots\ldots\ldots 0.013635(D_{n-1}+D_n)^2$$

or TTV= Volume 1 + Volume 2 + Volume 3 + ... Volume n

Where: TTV = Total tree volume in cubic feet.

D_1 = Diameter of the cross-sectional specimen at the 4.5 foot level.

D_2 = Diameter of the cross-sectional specimen at the 14.5 foot level.

D_3 = Diameter of the cross-sectional specimen at 24.5 feet and etc..

0.079085 = A constant obtained by clearing the constants in the expression for the volume of a cylinder representing the first log, i.e.;

$$\frac{\pi D^2 \text{(in inches) } 14.5 \text{ feet}}{4 \cdot 144}$$

and D= D_1 reduced by 3.574% to adjust the diameter at the 4.5 foot level to that at 7.25 feet.

0.013635 = A constant obtained by clearing the constants in the expression for the volume of a cylinder representing the second and subsequent logs, or;

$$\frac{\pi (D_2 + D_3)^2 \cdot 10 \text{ feet}}{4 \cdot 4 \cdot 144}$$

$$TTW = \text{Vol. } 1(62.43)\ \frac{\left| [SG_1 + 0.45(SG_1 - SG_2)] + SG2 \right|}{2} + \text{Vol. } 2$$

$$(62.43)\ \frac{(SG_2+SG_3)}{2} + \text{Vol. } 3\ (62.43)\ \frac{(SG_3 + SG_4)}{2} + \ldots$$

$$\text{Vol. } n(62.43)\ \frac{(SG_{n-1} + SG_n)}{2}$$

Where: TTW = Total tree weight (merchantable vol.) in pounds.

62.43 = The weight of one cubic foot of water in pounds.

$$\text{Density} = \frac{\text{TTW}}{\text{TTV}}$$

$$\text{Specific Gravity} = \frac{\text{Density}}{62.43}$$

Methods of statistical analyses

The initial computer program was designed to calculate the whole-tree specific gravity through the use of the weighting equation developed in the preceding section. Once this value was obtained it was punched into a new deck of cards along with the original tree data, plot data and core specific gravity. This operation made possible the combining of all cards representing the individual cross-sectional specimens into one card representing each tree for use in the multiple regression analysis.

A second program was developed to compute basic statistics on the data as well as make the necessary calculations for a series of one-way analyses of variance. These basic statistics include the mean, standard deviation, standard error of the mean and confidence intervals around the mean using the 95 percent level of confidence. These statistics were computed for the total number of specimens as well as for data segregated by diameter class, forest, plot and crown class. The segregated and overall statistics were computed for

whole-tree specific gravity, core specific gravity, cross-sectional specimen specific gravity, total tree age at breast height, rings per inch at breast height, total tree height, height to a five inch merchantible top and length of live crown. An analysis of variance was conducted with the above data using diameter class, forest, plot and crown class as the treatment effect.

Since one of the objectives of this study is to develop an equation for predicting whole-tree specific gravity with other easily measured variables, the writer calculated a number of simple linear regressions with this in mind. Through these regressions and other graphic relationships of the independent variables it was possible to more accurately arrive at those variables to use in a step-wise multiple regression analysis.

The step-wise multiple regression analysis was employed to develop the best predictive equation of whole-tree specific gravity. By using this procedure one can systematically arrive at the independent variables or combinations thereof that best predict whole-tree specific gravity. Using this method, one variable at a time is entered into the regression giving priority to that variable that reduces the variance of the dependent variable the greatest amount. This operation is repeated until the addition of the next variable, so selected, does not significantly reduce the unaccounted variance. The significance of the reduction in variance is determined by noting the calculated

"F-statistic" in comparison to a table value giving its theoretical distribution at a chosen level of significance.

Those variables used in the step-wise multiple regression to arrive at the most significant ones were:

Basic variables;

X_1... Basal area per acre.

X_2... Diameter breast height.

X_3... Total tree height.

X_4... Age at breast height.

X_5... Rings per inch.

X_6... Whole-tree specific gravity.

X_7... Core specific gravity.

X_8... Latitude.

X_9... Longitude.

X_{10}.. Elevation.

X_{11}.. Slope aspect.

X_{12}.. Topographic site.

Transformations;

X_{13}.. X_8X_{10}

X_{14}.. X_2X_3

X_{15}.. $(X_2)^2$

X_{16}.. X_4X_1

X_{17}.. $\frac{1}{X_4}$

X_{18}.. $\frac{X_2}{X_4}$

X_{19}.. $\frac{(X_{10})^2}{X_4}$

CHAPTER V

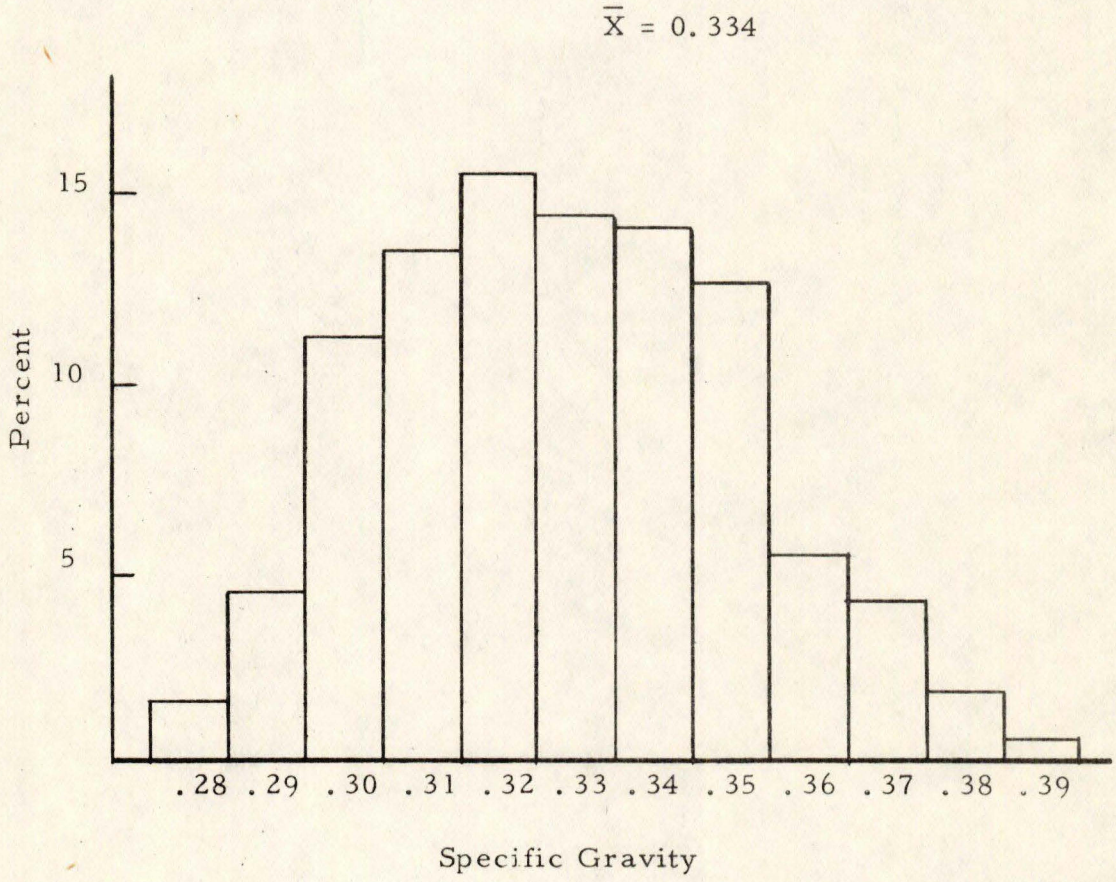
ANALYSIS OF DATA AND DISCUSSION

Whole-tree specific gravity

The average whole-tree specific gravity of the 316 trees destructively sampled is 0.334, based on the specimen's green volume and ovendry weight. Each whole-tree value was determined by weighting the cross-section specific gravity by the volume of wood each represented in the tree bole. The standard deviation for the measurements is 0.025 while the standard error of the mean is 0.0014. The values ranged from 0.258 to 0.409. The frequency distribution of the observations are depicted in figure 11. The magnitude of variation is well within the expected limits or coefficient of variation as defined in the Wood Handbook (99). This coefficient is defined as the standard deviation divided by the mean value and expressed as percent. For this data, the coefficient is 7.5 percent verses ten percent as suggested in the handbook for specific gravity measurements.

This specific gravity value of 0.334 for Engelmann spruce is an improvement of 0.014 over the presently accepted value (99). While the higher value resulted from 1720 cross-sections taken from 316 trees and sampled from 13 national forests, the accepted value was based on samples taken from 10 trees cut in two Colorado counties (46).

Figure 11.--Frequency distribution of 316 whole-tree specific gravity values.



In more recent research, Bodig and Troxell (8) indicated the average for the species should be close to 0.336 based on specimens taken from dimension lumber used in a stress grading study. The basic statistics for the whole-tree value are reported in table 1.

Correlation of whole-tree and increment core specific gravity

As a secondary objective of this study a prediction equation was to be developed for predicting whole-tree specific gravity using other easily-measured tree or wood characteristics. Of these characteristics, the specific gravity of an increment core extracted at breast height on the tree is the most significant, while being easily obtained. The average specific gravity of the 316 increment cores taken is 0.342, which is significantly different from the average whole-tree specific gravity. The significance of the difference is ascertained by employing the student's t test which resulted in critical regions of $t < -2.576$ and $t > 2.576$ at the one percent level of significance. The calculated t for the difference between the two means is -3.58, which is well within the left critical region and indicated rejection of the hypothesis that the two means are the same.

The results of simple linear regressions developed for predicting tree specific gravity are depicted graphically in figure 12. The prediction equation using core specific gravity is:

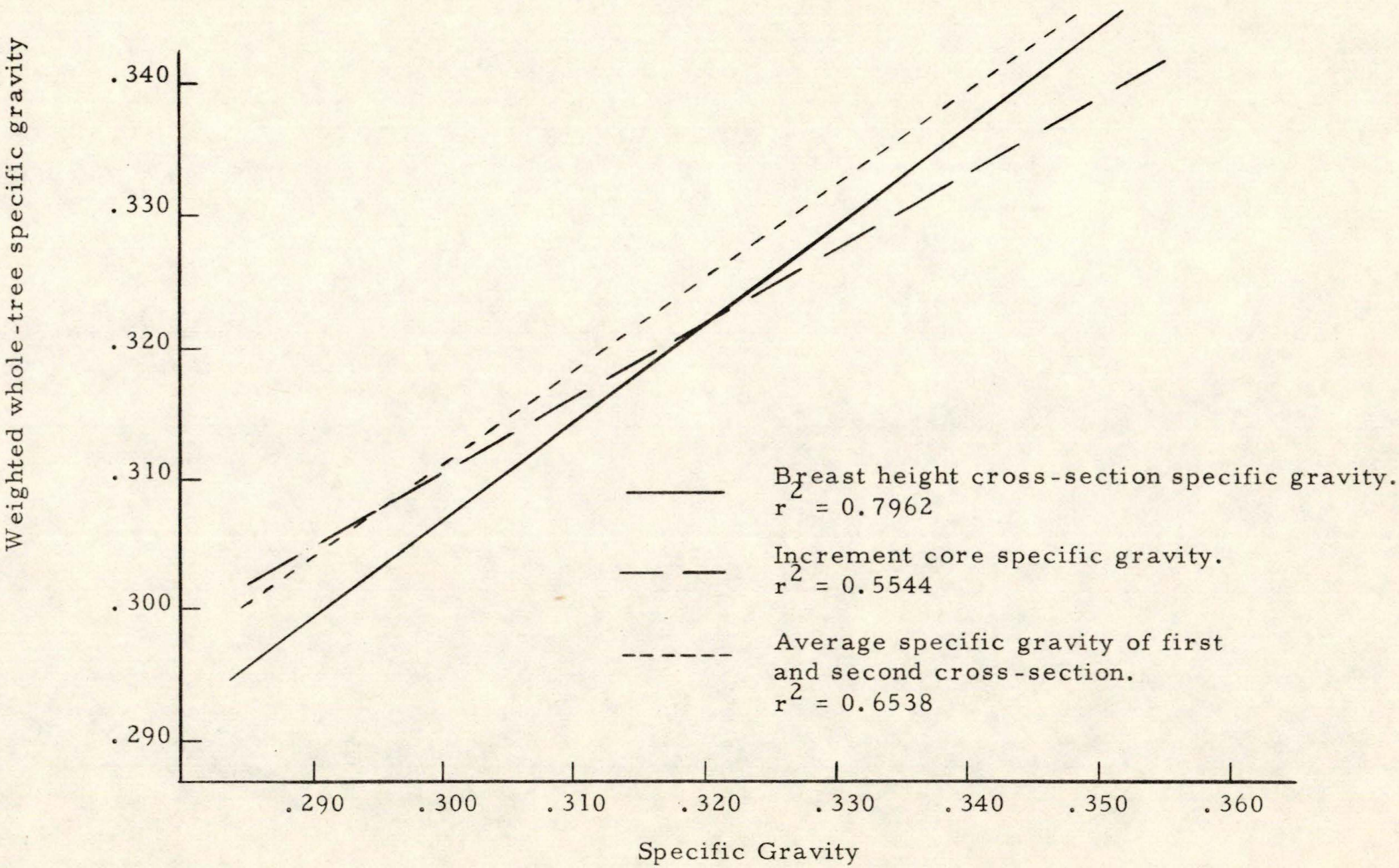
$$Y = 0.1458 + 0.5499x$$

$$r^2 = 0.5544$$

TABLE 1. --Basic statistics on tree, increment core and cross-sectional specimen specific gravity.

	N	Mean	sd.	Std. Error	95% Confidence Interval
Whole-tree specific gravity	316	0.334	0.025	0.0014	0.331-0.336
Core specific gravity	316	0.342	0.033	0.0019	0.338-0.346
4.5 foot level specific gravity	316	0.337	0.030	0.0017	0.333-0.340
14.5 "	314	0.330	0.030	0.0017	0.327-0.333
24.5 "	289	0.329	0.031	0.0018	0.325-0.332
34.5 "	248	0.331	0.031	0.0020	0.327-0.335
44.5 "	197	0.335	0.029	0.0020	0.331-0.339
54.5 "	138	0.341	0.049	0.0042	0.333-0.350
64.5 "	98	0.341	0.026	0.0027	0.336-0.347
74.5 "	56	0.348	0.024	0.0033	0.341-0.355
84.5 "	24	0.340	0.022	0.0044	0.330-0.349
94.5 "	9	0.351	0.017	0.0058	0.338-0.364

Figure 12. --Regression lines with tree specific gravity as predicted by three independent variables.



while the equation using the specific gravity of the breast height cross-section is:

$$Y = 0.08425 + 0.7410x$$

$$r^2 = 0.7962$$

Although the use of the breast height specimen accounts for a greater portion of the variation in whole-tree specific gravity it was not obtained through non-destructive sampling. The coefficient of determination using core specific gravity of 0.5544 compares favorably with those reported in studies on other species such as: Maeglin (45), Southern Wood Density Survey (76), Wahlgren and Fassnacht (88), Wahlgren, et al. (89), and the Western Wood Density Survey (97).

Specific gravity variation with tree diameter at breast height

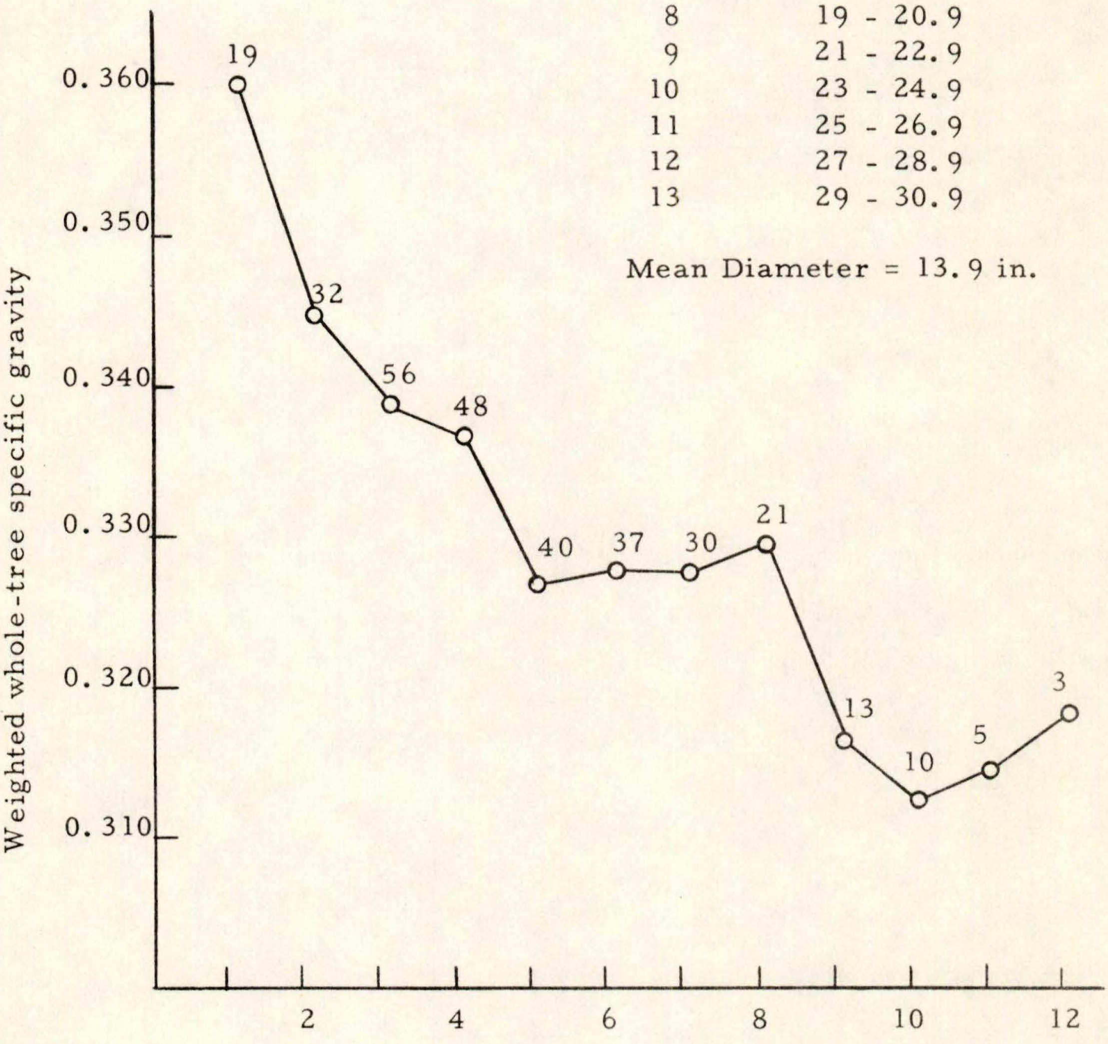
For Engelmann spruce, whole-tree specific gravity tends to decrease with increasing tree diameter. This trend is graphically presented in figure 13 where the mean specific gravity is plotted by diameter classes. Research with other softwoods indicates the opposite behavior since it is generally accepted that specific gravity increases from the pith outward (14, 30, 58, and 100). In a limited investigation, this writer, by segmenting 21 increment cores, found specific gravity to decrease from the pith outward. This investigation is discussed at the end of this section and is mentioned here since it supports the decrease in specific gravity with increasing tree diameter.

Figure 13. --Specific gravity of the thirteen diameter classes.

The number associated with each point represents the number of observations.

Diameter Class	D. B. H.
1	5 - 6.9
2	7 - 8.9
3	9 - 10.9
4	11 - 12.9
5	13 - 14.9
6	15 - 16.9
7	17 - 18.9
8	19 - 20.9
9	21 - 22.9
10	23 - 24.9
11	25 - 26.9
12	27 - 28.9
13	29 - 30.9

Mean Diameter = 13.9 in.



The results of a simple linear regression using whole-tree specific gravity as the dependent variable and breast height diameter as the independent variable, indicates a negative relationship does exist but not to the extent suggested in figure 13. The resulting regression line has a slope of only -0.00005 while the coefficient of determination is 0.1688. A reasonable explanation for the near horizontal line is the decreasing number of observations at the extreme ends of the diameter range, especially for trees having large diameters. The following table breaks out the sum of squares due to regression.

TABLE 2.--Analysis of variance summary for linear regression on whole-tree specific gravity as predicted by tree diameter.

Source	D.F.	S.S.	M.S.	F.
Total	315	0.1906		
Regression	1	0.0322	0.0322	64.5** [1]
Residual	314	0.1584	0.0005	

The F value can be used to test that b (slope) of the regression line is equal to 0. Because of the large F we can reject this hypothesis, accepting that a regression does exist.

[1] In presenting analysis of variance tables, a double asterisk signifies significance at the one percent level, a single asterisk signifies significance at the 5 percent level and N.S. denotes no significance.

A preliminary calculation of a one-way analysis of variance on the specific gravity by diameter classes indicated a significant difference between diameter classes. This technique tells us a difference does exist somewhere among the 13 classes. The following is a summary table of this analysis.

TABLE 3.--Analysis of variance summary of whole-tree specific gravity by diameter classes.

Source	D.F.	S.S.	M.S.	F.
Total	315	.1906		
Treatment	12	.0351	.0029	5.705**
Residual	303	.1555	.0005	

To more specifically isolate where the differences between diameter classes exist, a specific test involving a linear combination was employed. Here the significance of the difference between the average of the smallest three diameter classes and the largest three diameter classes is tested. The statistical procedure used to evaluate the difference is described by Li, (43). A 99 percent confidence interval was constructed for the linear combination which resulted in limits of 0.015 and 0.055. Since zero does not fall within the interval, the difference between the averages of the extreme three means is significant at the one percent level. By using the confidence interval

approach it can be stated that 99 percent of the time the difference between the mean of the smallest three diameter classes and that of the largest three can be expected to be within the range of 0.015 and 0.055. Table 4 lists the mean specific gravity by diameter classes.

Specific gravity variation at various height levels in the tree

In figure 14, the mean specific gravity of specimens collected at the various height levels is graphically presented. The mean specific gravity at breast height is slightly greater than the average whole-tree specific gravity for the species. From breast height to 25 feet up the bole there is a marked decrease, at which level it steadily increases for the next forty feet. Above the 75 foot level the specific gravity tends to decrease once again, however, the number of observations declines quite rapidly for the higher level specimens. The basic specific gravity statistics for the specimens taken at the various height levels are reported in table 1 while they are reported by diameter classes in table 4. The relationship illustrated in figure 14 is consistent with that reported by others. Collett (14), in a similar study on lodgepole pine found that specific gravity decreased sharply in the initial ten feet of bole length while the following forty feet it remained reasonably constant. Above fifty feet it began increasing steadily. This same general trend has been reported by Krahmer (41) for western hemlock and by Wahlgren *et al.* (89) for black spruce grown in Maine.

TABLE 4. --Average measurements by diameter classes.

	Diameter Class												
	1	2	3	4	5	6	7	8	9	10	11	12	13
No. of trees	19	32	56	48	40	37	30	21	13	10	5	3	2
Whole Tree sp. gr.	.360	.345	.339	.337	.327	.328	.328	.330	.317	.313	.315	.319	.305
Core sp. gr.	.395	.363	.348	.345	.335	.333	.335	.331	.304	.312	.308	.306	.289
Rings per inch	40.8	32.8	27.8	26.4	23.6	30.8	25.9	26.2	18.4	18.7	16.1	24.3	16.9
Age (years at BH)	121	120	126	140	143	203	192	211	165	196	186	282	229
Total height (ft.)	42	51	57	64	71	79	87	87	98	99	103	102	113
Sp. gr. at 4.5 ft.	.382	.352	.340	.341	.330	.327	.330	.334	.316	.303	.318	.307	.303
" 14.5 ft.	.359	.339	.338	.332	.323	.327	.324	.320	.327	.291	.303	.333	.299
" 24.5 ft.	.336	.340	.338	.336	.325	.325	.328	.319	.306	.323	.310	.311	.299
" 34.5 ft.		.347	.349	.336	.327	.330	.325	.333	.310	.304	.312	.316	.300
" 44.5 ft.		.331	.346	.338	.335	.335	.335	.336	.318	.336	.319	.328	.305
" 54.5 ft.			.362	.350	.339	.338	.340	.358	.328	.350	.322	.324	.311
" 64.5 ft.				.347	.345	.350	.337	.343	.347	.335	.330	.331	.317
" 74.5 ft.					.372	.372	.351	.341	.345	.343	.352	.350	.325
" 84.5 ft.							.335	.338	.338	.349	.339	.355	.338
" 94.5 ft.								.346	.344	.351	.358	.361	.349

Diameter class codes

1 = 5- 6.9 in.	5 = 13-14.9 in.	8 = 19-20.9 in.	11= 25-26.9 in.
2 = 7- 8.9 in.	6 = 15-16.9 in.	9 = 21-22.9 in.	12= 27-28.9 in.
3 = 9-10.9 in.	7 = 17-18.9 in.	10= 23-24.9 in.	13= 29-30.9 in.
4 =11-12.9 in.			

Figure 14.--Specific gravity at the various height levels above the ground.

The number associated with each point represents the number of observations.

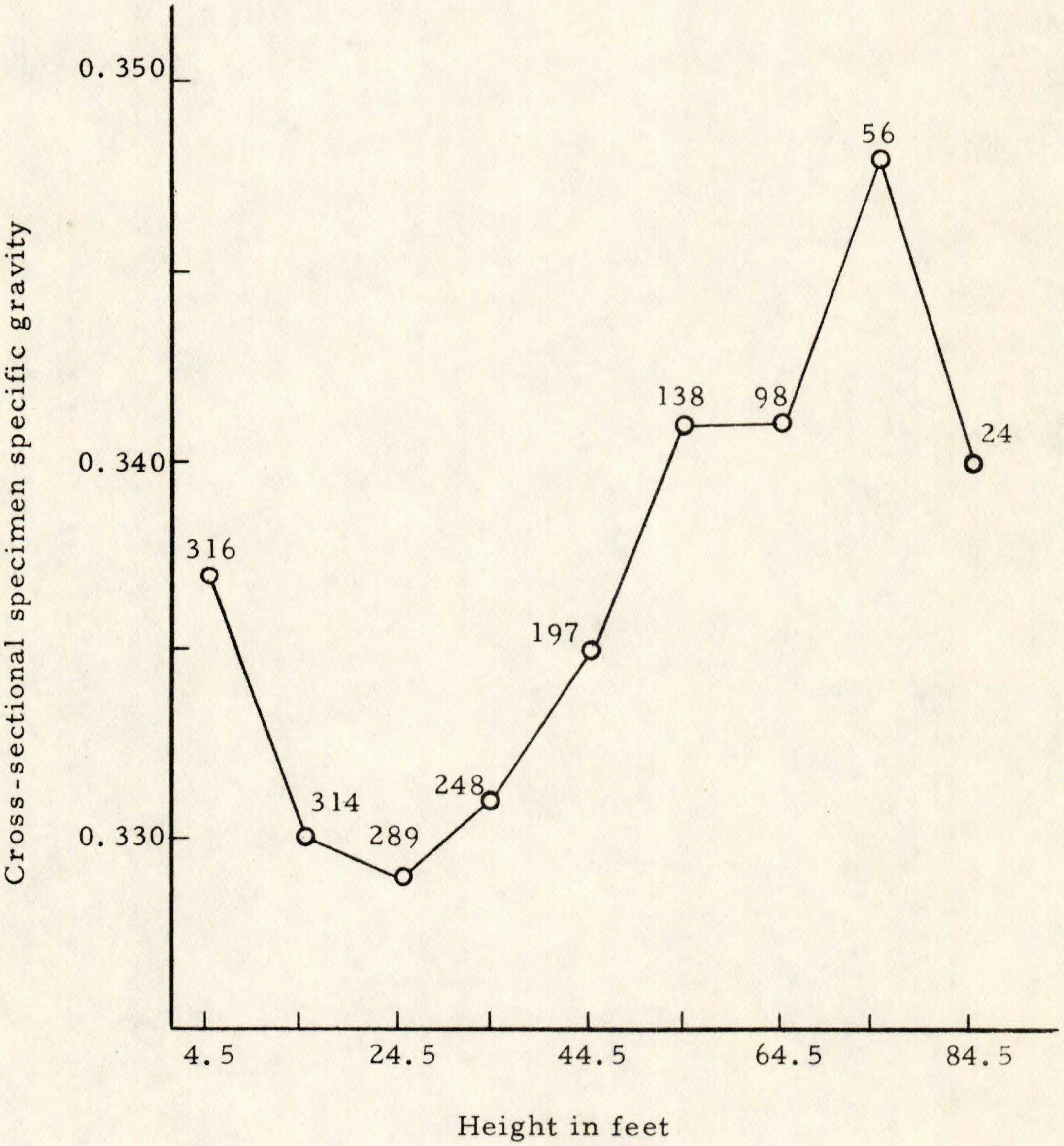


Figure 15 depicts the changes in specific gravity with increasing tree height by diameter classes. It can be observed from studying this figure that the lower level specific gravity in small trees is considerably higher than the lower level specific gravity of larger diameter trees. Since the major wood volume exists in the lower portion of the tree, large trees would reduce effectively the average whole-tree specific gravity for the species. This supports the sampling method used in this study whereby the number of trees sampled in each diameter class was governed by the total volume in each class as projected by forest inventory. Therefore, the whole-tree specific gravity average is more realistically estimated by the diameter class weighting.

Specific gravity variation with tree age

The age of each sample tree was determined by a growth ring count on the cores extracted at breast height. While the mean age of the 316 trees was 157 years, the values ranged from 38 to 424 years at breast height. No attempt was made to project this age to zero feet to report total tree age. Alexander (2) in work resulting in the development of site index curves for Engelmann spruce, found the initial period of tree adjustment to be 20-40 years for free growing spruce while suppressed trees may require 100 years. Thus, no reliable figure exists for estimating the age of this species to achieve a height of 4.5 feet.

Figure 15. --Specific gravity variation with height level by diameter classes.

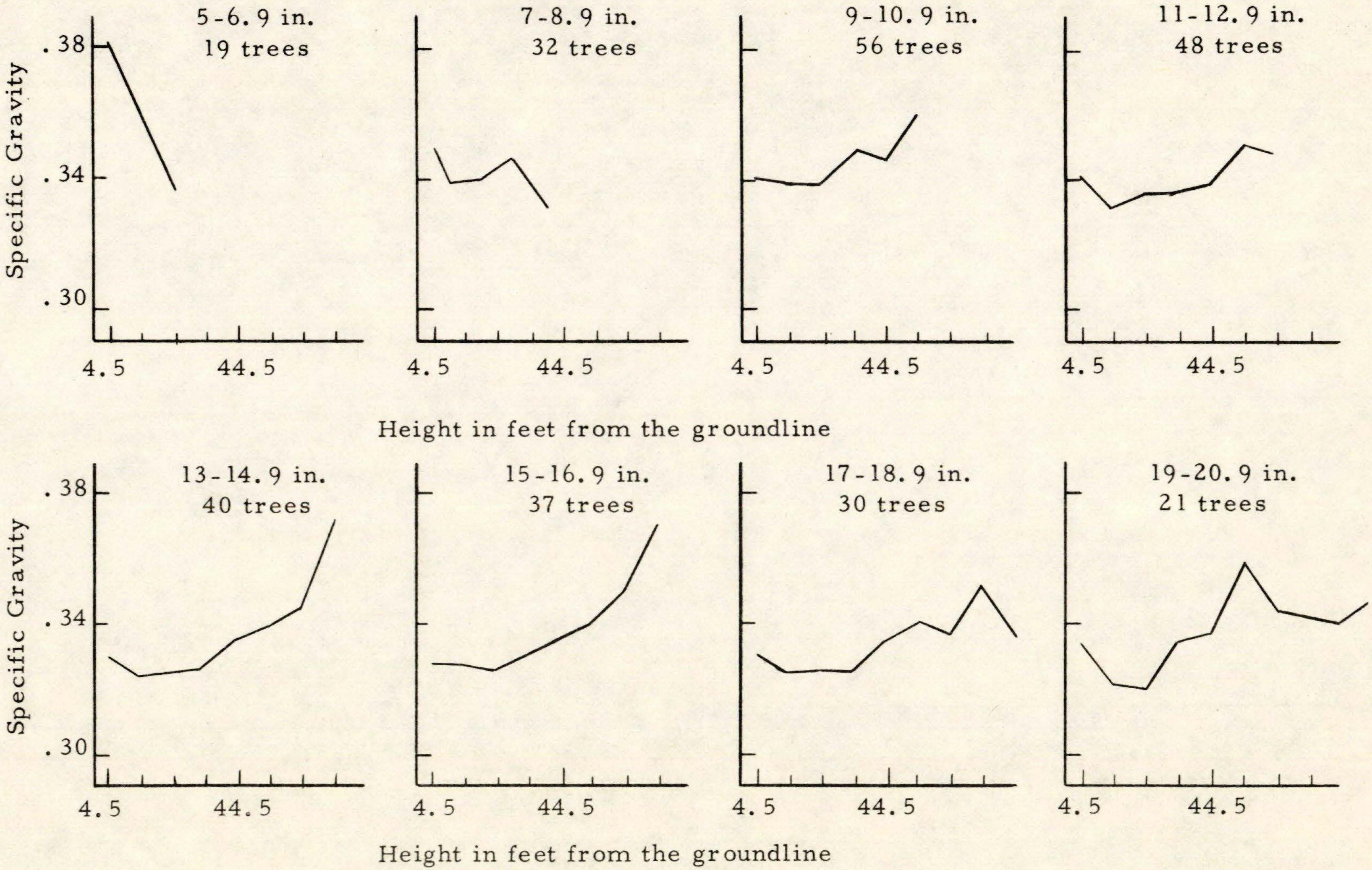
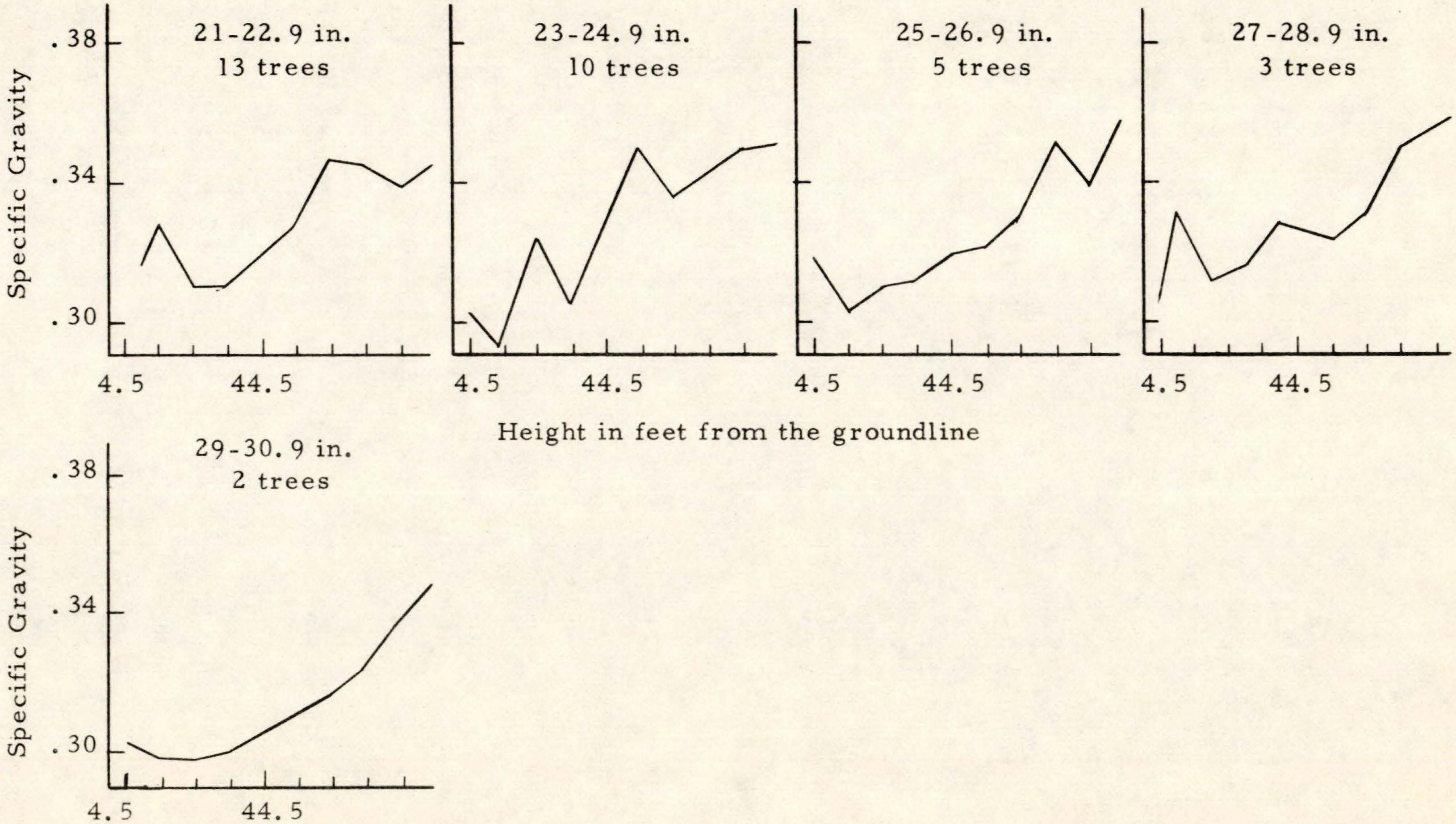


Figure 15. --Continued



The basic statistics for tree age at breast height as measured on the 316 increment cores are reported in table 5. Mean age by diameter class is reported in table 4. In figure 16, age at breast height is plotted against the breast height cross-section specific gravity. Figure 17, illustrates the graphic relationship between age and diameter. It was previously concluded that increased tree diameter results in a decrease in specific gravity. Obviously one would expect age to increase with increased tree diameter. With this analogy one would then expect specific gravity to decrease with tree age. This is not the case when specific gravity and age are plotted at breast height, figure 16. From figure 16 a slight increase in specific gravity is found with increased age. Although the regression line is nearly horizontal the regression is significant at the one percent level. This simple linear regression produces a coefficient of determination of 0.0599 or 5.99 percent of the variation in specific gravity is accounted for by age. The age measurements have a considerable variance. Examining the standard deviations by diameter classes one notes the smallest deviation of 21.2 exists in the 29-30.9 inch class where only two trees were measured. The diameter class of 9-10.9 inches had the largest number of observations (56), and the standard deviation is 111.7 years. As a matter of course, a one-way analysis of variance was carried out between the age observations by diameter class. Naturally, a significant difference resulted. For the summary

TABLE 5. --Average measurements on trees

	N	Mean	Std. Dev.	Std. Error	95% Confidence Intervals
Tree Diameter	316	13.900			
Tree Height	316	70.760	25.991	1.462	68.216-74.006
Height to a 5 inch top	316	53.223	21.499	1.209	50.829-55.618
Length of live crown	316	47.051	15.294	0.860	45.348-48.755
Age (yrs. at B.H.)	316	157.032	86.605	4.872	147.385-166.678
Rings per inch	316	27.436	17.110	0.963	25.530-29.342
Elevation	40	10,333			(Range) 8,200-11,800

Figure 16. --Regression line for specific gravity and age at breast height.

$r^2 = 0.0599$

$Y = 0.32564 + 0.00007 X$

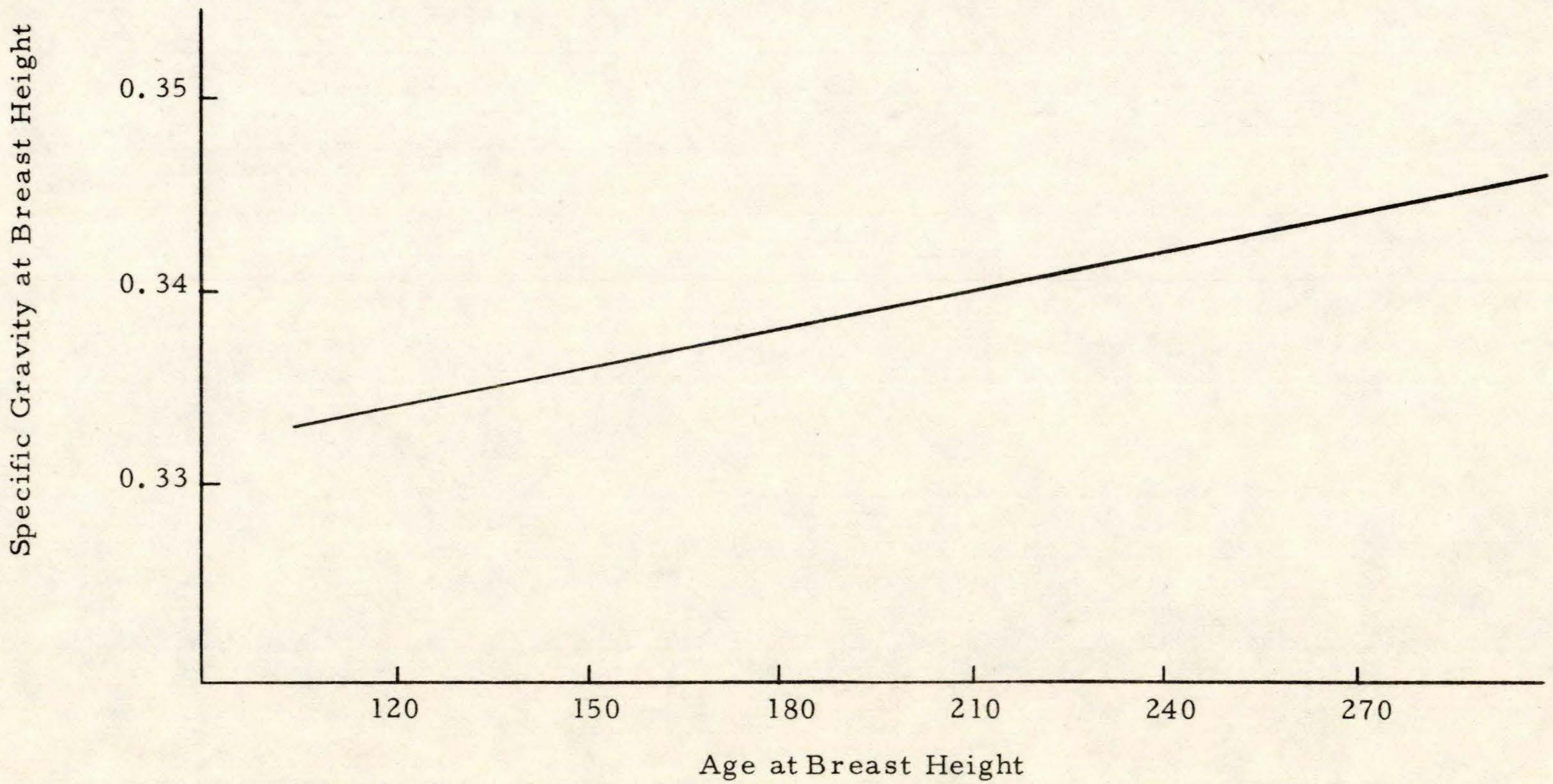


Figure 17. --Regression line for age at breast height and diameter class.

$r^2 = 0.7235$

$y = 104.12 + 10.54\ X$

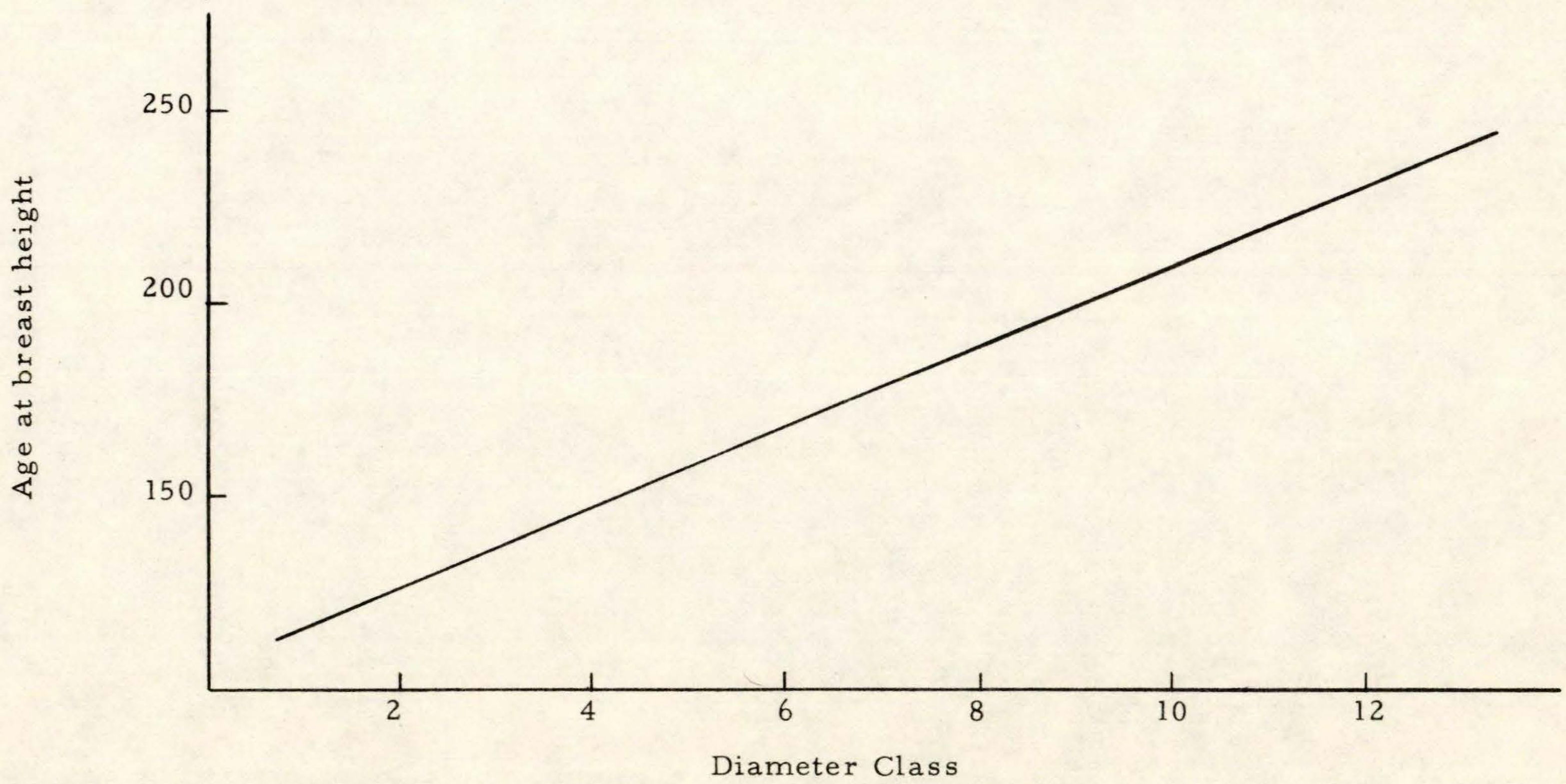


table of the analysis see table 6. In the step-wise multiple regression, discussed later in this chapter, the variable age was entered as the sixth variable in order of significance in accounting for variation in whole-tree specific gravity. The entry of age only increased R^2 (multiple correlation coefficient) by 0.0016 or accounted for an additional 0.16 percent of the variation in whole-tree specific gravity.

TABLE 6. --Analysis of variance summary on age observations by diameter classes.

Source	D. F.	S. S.	M. S.	F.
Total	315	2, 362, 653.7		
Treatment	12	397, 201.5	33, 100. 1	5. 1**
Residual	303	1, 965, 452. 2	6, 486. 6	

Specific gravity variation with rings per inch

The average rate of growth for the 316 sample trees is 27.4 rings per inch. The growth rates for the sample trees ranged from 7.7 to 118 rings per inch. The basic statistics for this property are reported in table 5 while the means by diameter classes are reported in table 4. The most rapid overall rate of growth of 16. 1 rings per inch occurred in the 25-26. 9 inch diameter trees while the slowest occurred in the smallest class or those 5-6. 9 inches in diameter. Rings per inch are generally correlated with specific gravity. For

conifers, the greater the number of rings per inch, the higher the volume of summerwood which is the more dense portion of the annual growth increment. Increased growth rate generally results in an increase in the proportion of springwood or the less dense portion of the growth increment. The rate of growth for the trees sampled follows a similar pattern to the specific gravity of the breast height specimen when plotted by diameter classes, figure 18. The extremes of rate of growth are plotted against whole-tree specific gravity in figure 19. Three trees having in excess of 100 rings per inch were excluded from the figure. It should be pointed out that the extremes plotted represent 88 trees leaving 225 trees with values between 13 and 40 rings per inch. A slight trend is evident in figure 19 towards and increased specific gravity with an increase in rings per inch. Simple linear regression produces an r^2 of 0.1731 or considered alone, rings per inch account for 17.3 percent of the variance in tree specific gravity. A one-way analysis of variance on rings per inch by diameter class indicates a significant difference does exist between diameter classes at the one percent level, however, the computed F value is small at 2.4. This analysis of variance summary table is recorded in table 7. This variable was second to be added in the multiple regression and accounted for 1.19 percent of the variance in whole-tree specific gravity.

Figure 18. --Rings per inch and specific gravity at breast height plotted by diameter classes.

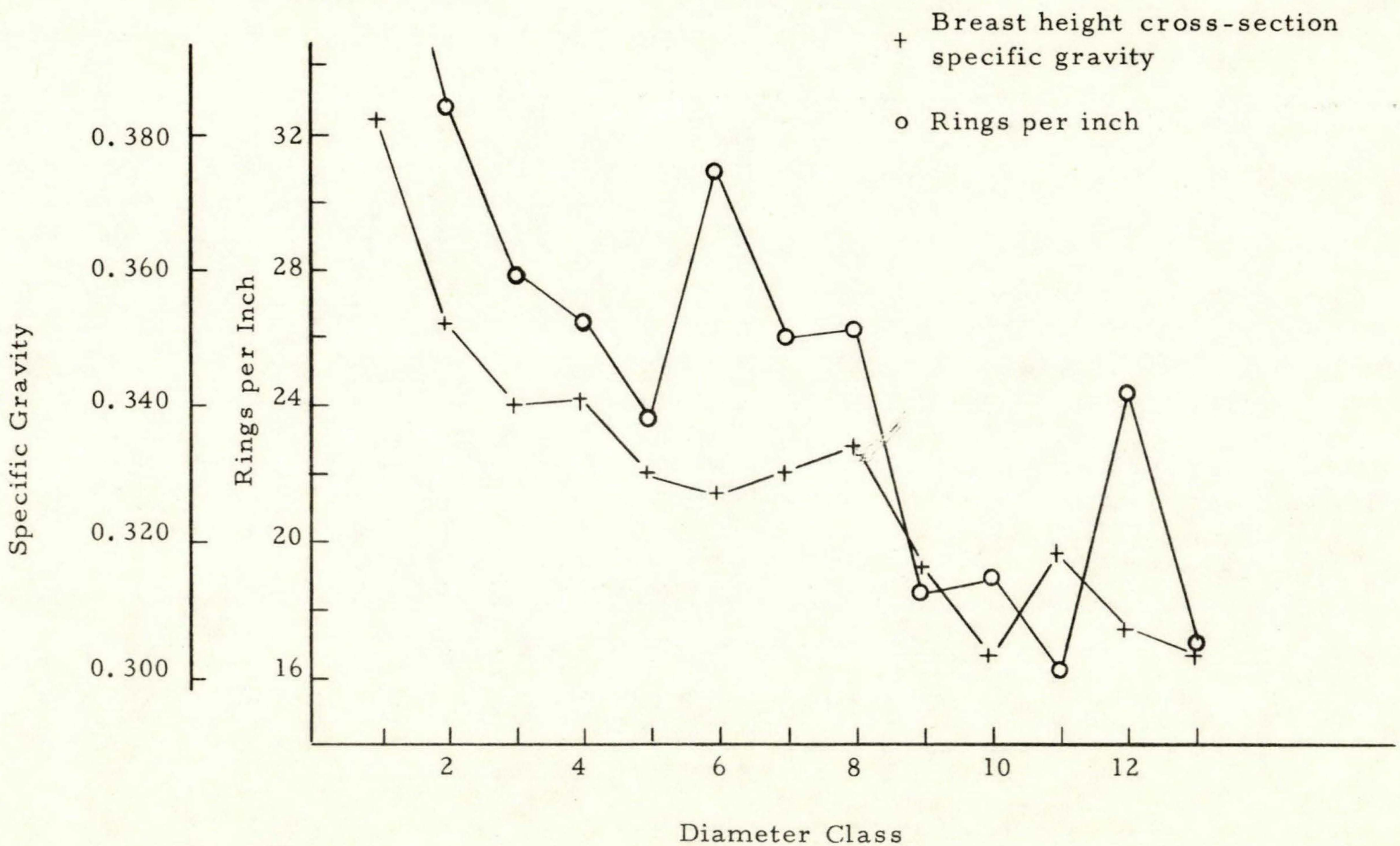


Figure 19.--Whole-tree specific gravity with average rings per inch at breast height for those trees having less than 13 and more than 40 rings per inch.

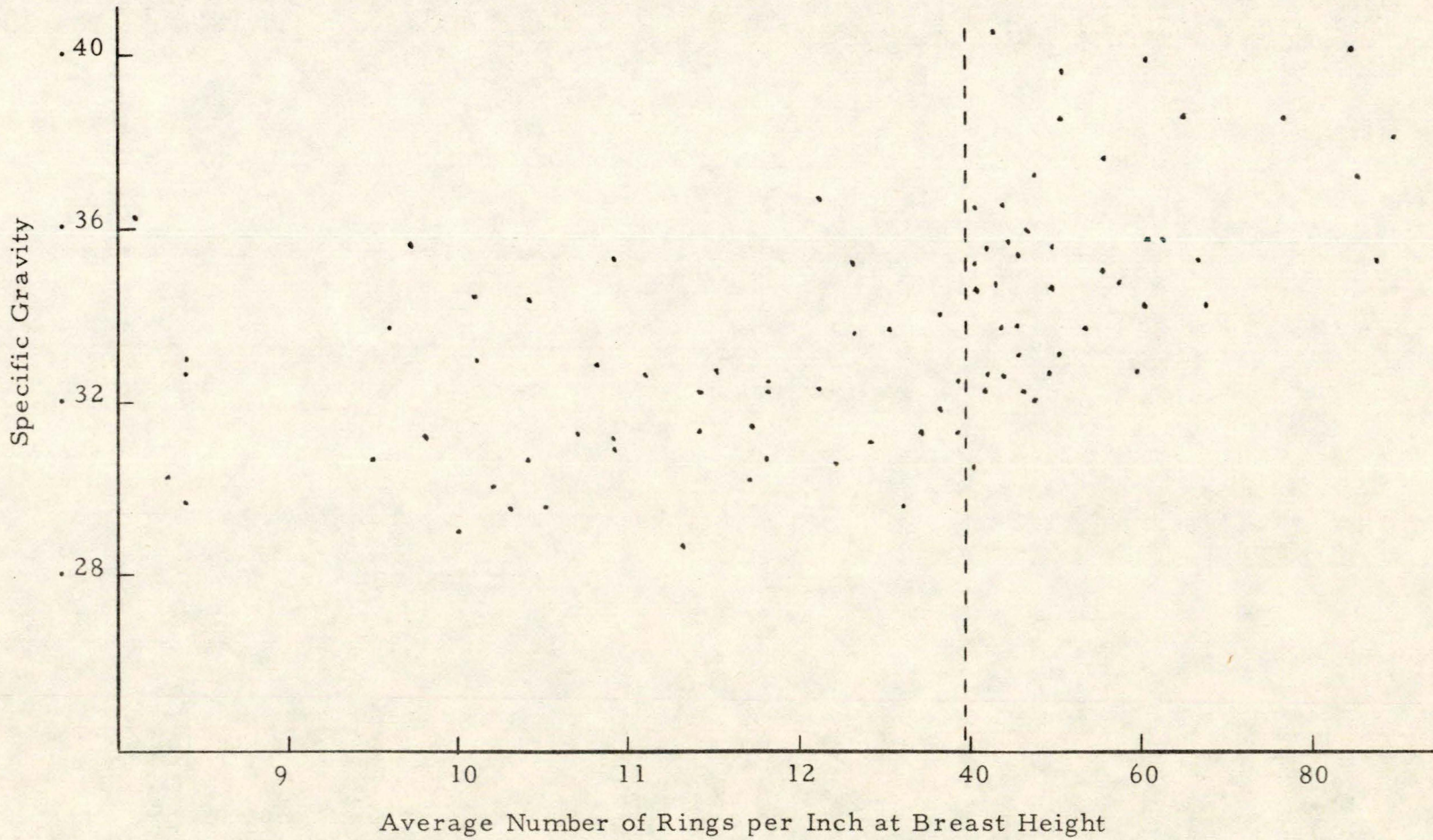


TABLE 7.--Analysis of variance summary on rings per inch by diameter classes.

Source	D.F.	S.S.	M.S.	F.
Total	315	92,218.6		
Treatment	12	8,160.7	680.1	2.4**
Residual	303	84,057.8	277.4	

The effect of elevation on specific gravity

The elevation at each cutting area[1], was eatimated to the nearest 100 feet from contour maps of the area. Since some of the cutting areas occurred where land surveys have not been completed, topographic maps were not available for all plots. Therefore, elevation data is not available for eight of the cutting areas. Due to the missing data, the average whole-tree specific gravity by cutting areas having corresponding elevation data were used in illustrating specific gravity-elevation relationships. This results in the omission of 52 of the 316 trees sampled. Considering elevation alone, its affect on whole-tree specific gravity is illustrated by a linear relationship shown in figure 20. Although the change is not abrupt, the slope of the regression is significantly different from zero. The data necessary for this test

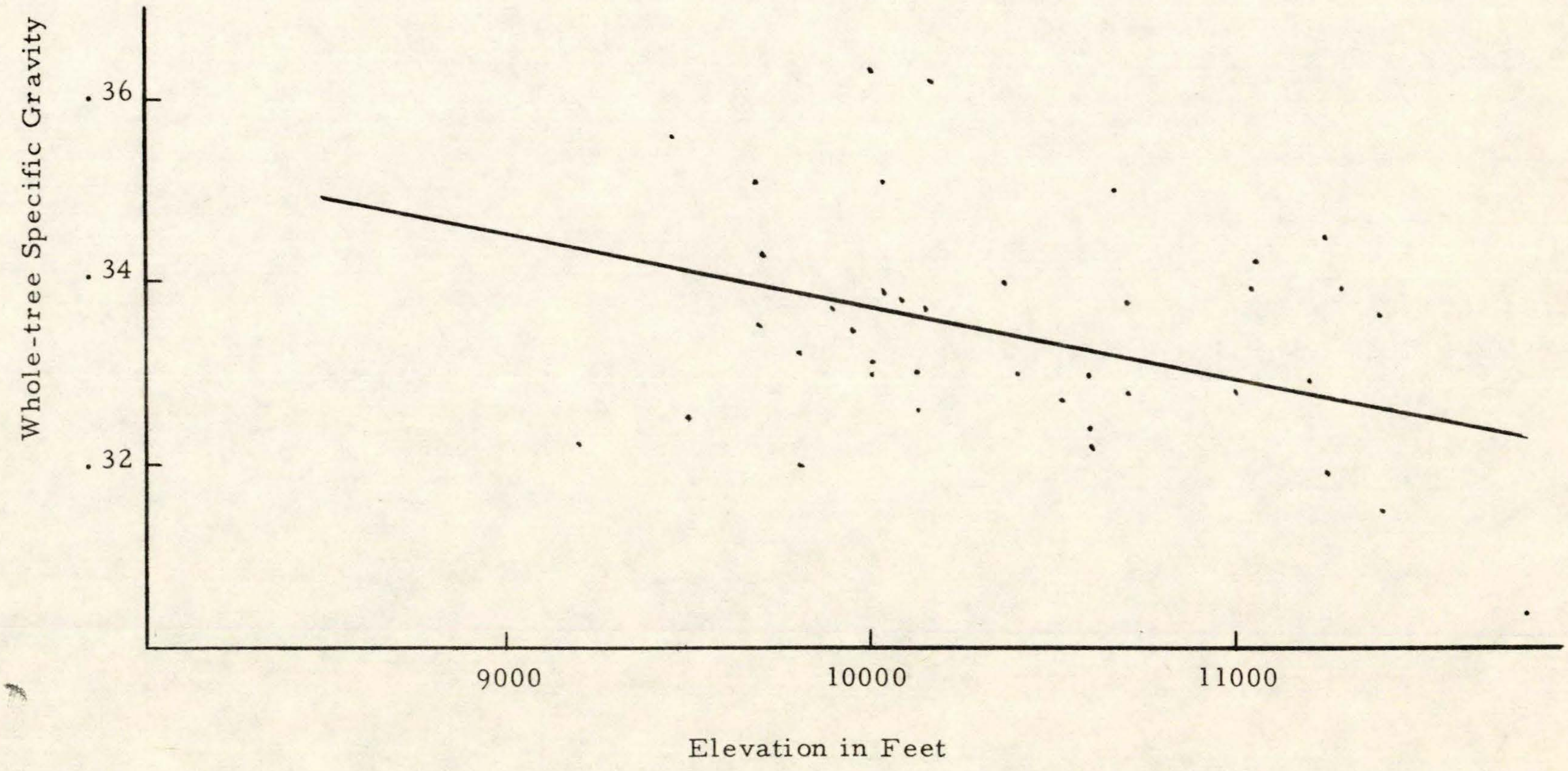
[1] Throughout this discussion, the term "cutting area" refers to the location making up two cutting plots, two chains apart. Due to the proximity of the two cutting plots, the elevation and latitude data is the same for both plots.

Figure 20. --Regression line for elevation and average whole-tree specific gravity by cutting area.

$Y_2 = 0.417477 - 0.000008\ X$

$r^2 = 0.1865$

$b = -0.000008$



is reported in table 8. In figure 21, the decrease in specific gravity with increased elevation is illustrated by the plotting of the mean specific gravity between elevation intervals of 1000 feet. The evident decrease in specific gravity with increased elevation is not surprising. In terms of climatic differences one would expect shorter growing seasons, cooler temperatures and lower soil depths at higher elevations. High winds, too, are believed to hinder growth due to an increased rate of transpiration. It must be emphasized, that a number of other variables and their interaction with elevation must be considered in viewing these simple relationships.

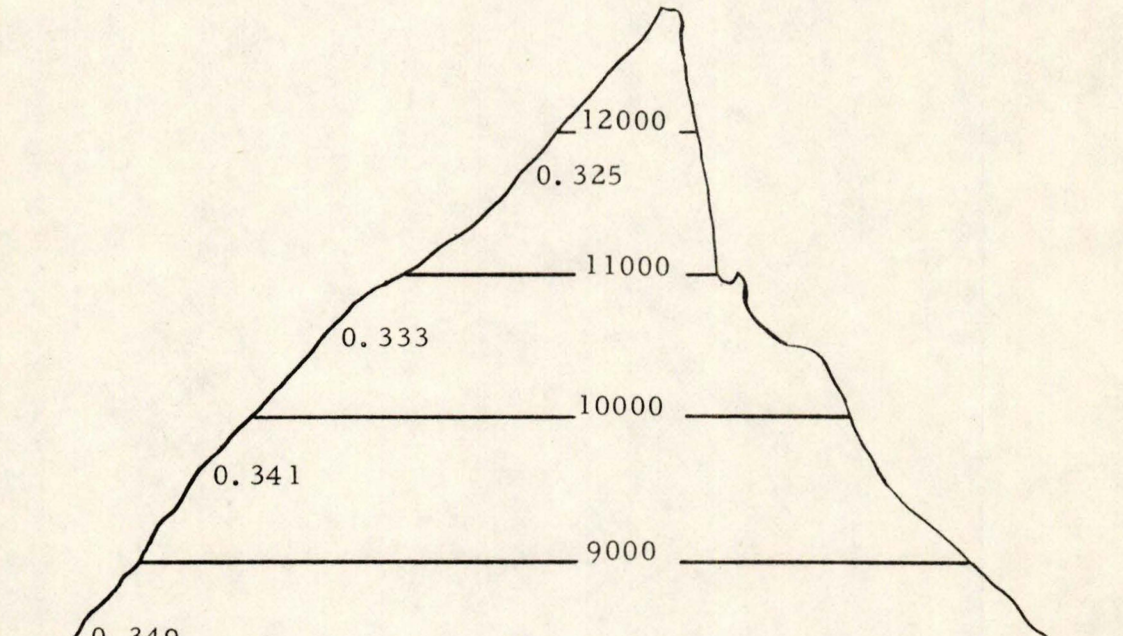
TABLE 8. --Analysis of variance summary for testing the significance of the regression (elevation with specific gravity).

Source	D.F.	S.S.	M.S.	F.
Total	38	0.006117		
Regression	1	0.001141	0.001141	8.51**
Residual	37	0.004976	0.000134	

Specific gravity variation due to latitude changes

As with elevation, the latitude of each cutting area was estimated to the nearest minute from topographic maps. To ease the computations, the minutes were converted to the decimal equivalent in degrees. The affect of latitude alone on tree specific gravity is

Figure 21. --Mean specific gravity differences between elevation isoplethes at 1000 foot intervals.



demonstrated in figure 22. The area void of points between 42 and 43 degrees represents that portion of Wyoming where no sample plots were taken. If the effect of other variables that are associated with latitude can be set aside there exists an interesting relationship. It can be noted from figure 22 that for each degree change in latitude specific gravity changes by 0.003 units. The mean latitude of the 47 cutting areas in this study, producing a mean whole-tree specific gravity of 0.334, is 39.05 degrees. In projecting this mean specific gravity to Lewiston, Idaho, the approximate seven degrees difference in latitude would result in a specific gravity there of 0.355. Potlatch Forests, Inc., reported a value for the species of 0.350 based on 114 samples (77). Similarly, Kennedy (39) reported a value of 0.38 for Canadian Engelmann spruce. Assuming an 11 degree difference in latitude the projection from this data would yield a specific gravity value of 0.367 in central British Columbia. This relationship would certainly support the validity of increased strength figures for Canadian Engelmann spruce (39). It would also provide a rational explanation for the low specific gravity value shown in the Wood Handbook (99), since their value is based on a sample taken from the Southern part of Colorado.

Other variables and specific gravity

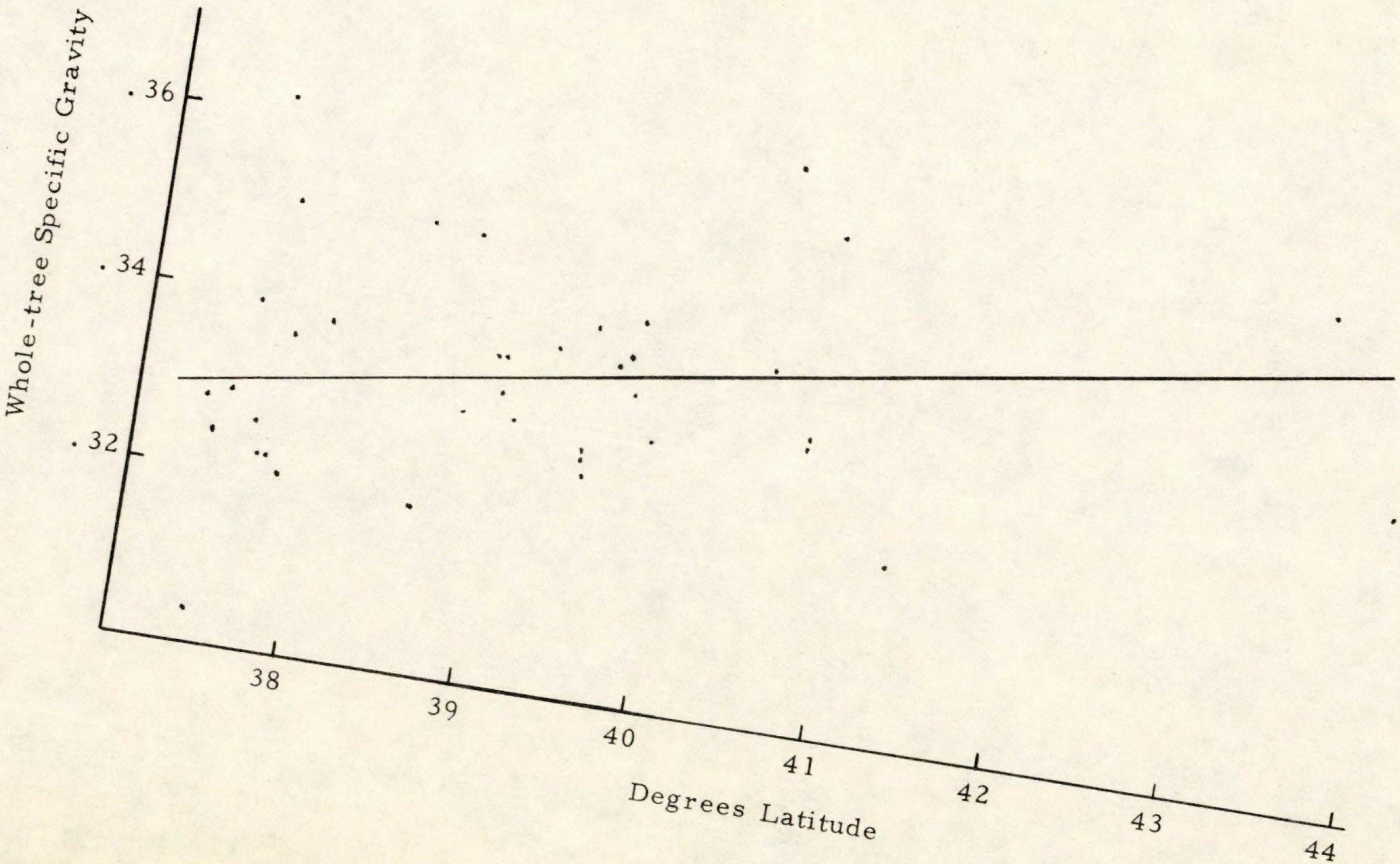
A significant difference in specific gravity was found between forests. The summary table of a one-way analysis of variance

Figure 22.--Regression line for latitude and average whole-tree specific gravity by cutting area.

$$Y = 0.214146 + 0.003087\,X$$

$$r^2 = 0.1437$$

$$b = 0.003087$$



between whole-tree specific gravity segregated by forests is reported in table 1 of appendix B. This difference is not surprising due to the observed differences between the size of trees and growth rate between forests. Some differences should also be expected between the forests of southern Colorado and northern Wyoming due to the change in latitude. The means of the basic variables are segregated by forests and reported in table 2 of appendix B.

One of the variables significantly related to whole-tree specific gravity in the multiple regression analysis (discussed later in this paper) is topographic site. This is difficult to explain since topographic site was simply a classification from 1 to 6 categorizing the terrain of the cutting areas. In order of magnitude the codes stand for flat, gentle slope, moderate slope, steep slope, creek bottom, and mountain top. In multiple regression, whole-tree specific gravity was associated with the code numbers and the output indicates specific gravity increases with an increase in code magnitude. One would expect trees from creek bottoms (code 5) to have a more rapid rate of growth than those from steep slopes (code 4) and mountain tops (code 6) due to the differences in available moisture. In looking at the effect of rings per inch, higher specific gravity is associated with reduced growth rate. Therefore, perhaps codes 4 and 6 produced a significant affect on specific gravity due to growth rate alone. Although this variable is significantly associated with specific gravity

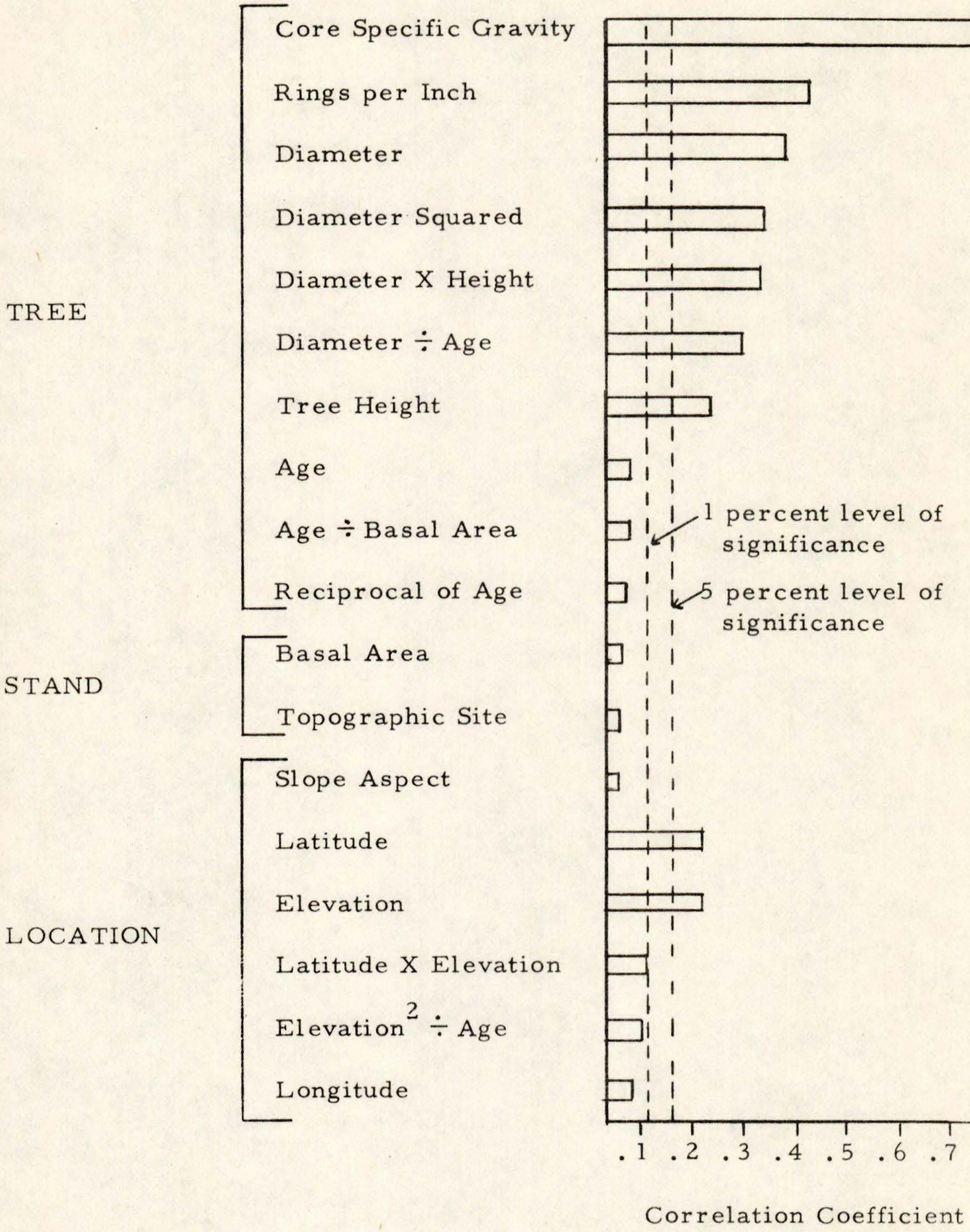
in regression, it only accounts for an increase of 0.88 percent of the variance in specific gravity. In simple linear regression with whole-tree specific gravity the variable only accounts for 0.26 percent of the variation.

Specific gravity differences were also detected between dominant and codominant trees. In the field, the trees were classified as dominant when no crown competition was evident. All other trees were classed as codominant since no suppressed trees were sampled. The means of the various variables are segregated by crown classes and reported in table 3 of appendix B.

Multiple regression analysis

The purpose of using the step-wise multiple linear regression technique is to determine the best combination of the variables measured or transformations thereof, for predicting whole-tree specific gravity. The procedure for multiple regression is described on page 44. Of the eleven independent variables used in multiple regression, five were measures of the tree itself, two were variables of the stand and four were measures of the cutting area location. In addition to the eleven basic variables, seven transformations were used as listed on page 45. The correlation of each of the independent variables with whole-tree specific gravity is shown graphically in figure 23. The broken lines in figure 23, marking the one and five percent levels of significance, serve to illustrate that the same variables are

Figure 23.--Relationship between whole-tree specific gravity and each of the variables tested.



significant at both levels. All the simple correlation coefficients are reported in table 2 of appendix C, as well as the inter-correlations between variables. It should be pointed out that the simple linear correlation coefficients reported in table 2 of appendix C do not agree precisely with those for the same two variables reported earlier in this paper. For example, the simple correlation coefficient for whole-tree specific gravity with core specific gravity in figure 12 is 0.7446 while the same two variables in table 2, appendix C, show a correlation coefficient of 0.7562. This difference is a result of missing elevation data for eight cutting areas. Therefore, in order to include elevation as one of the independent variables in multiple regression, only the data from 264 trees from 39 of the 47 cutting areas could be used. The previously reported regressions were computed from the total or 316 trees.

The initial multiple regression analysis resulted in the selection of 4 of 18 variables included as being significantly related to whole-tree specific gravity at the ten percent level of significance. It is interesting to note that these four variables; core specific gravity, rings per inch, topographic site, and elevation are also significant at the one percent level. The simple correlation coefficients of the four significant variables with whole-tree specific gravity and all inter-correlations are reported in table 9.

TABLE 9. --Simple correlation coefficients and inter-correlations for the four significant independent variables in predicting whole-tree specific gravity.

	Core specific gravity	Rings per inch	Site	Elevation
Whole-tree specific gravity	0.756	0.416	0.051	-0.229
Core specific gravity	1.000	0.419	-0.070	-0.219
Rings per inch		1.000	0.066	-0.012
Site			1.000	0.192
Elevation				1.000

In the step-wise procedure, the first variable brought into the equation is the most significant one in linear relationship to whole-tree specific gravity. The first variable was core specific gravity with a simple correlation coefficient of 0.756. The selection of the second and subsequent variables does not depend upon the simple linear relationship, i.e., the second variable entered does not necessarily have the next highest simple correlation coefficient. The selection is governed by which variable in combination with core specific gravity produces the greatest reduction in the unaccounted variance in whole-tree specific gravity. The second variable added was rings per inch, the third variable was topographic site, and the fourth was elevation.

While the second variable added had one of the highest simple correlation coefficients, the third variable was one of the least correlated with whole-tree specific gravity by itself. As each variable is added in multiple regression an F test is conducted to determine if the combined variables still maintain a significant regression relationship with the dependent variable, in this case, whole-tree specific gravity. The prediction equations using the four significant variables are reported in table 10.

Although the latter three variables when added in multiple regression, maintain a significant regression relationship at the one percent level of significance they do not appreciably increase the total accounted for variance in whole-tree specific gravity. The magnitude of the increases are reported in table 11. The contribution of each added variable in accounting for the variance in whole-tree specific gravity are reported in the last column of table 11. While core specific gravity accounts for 57.19 percent of the variation, the other three variables only increase the value by 2.94 percent. From the standpoint of practicality an equation involving only core specific gravity is nearly as good as one containing all four of the significant variables or:

$$\underline{Y = 0.13986 + 0.56767 \text{ (core specific gravity)}}$$

When the multiple regression technique is used it is necessary to determine if any important transformations of the significant

TABLE 10. --Successive step-wise multiple regression equations using the four significant variables.

Step 1. Whole-tree specific gravity as predicted by core specific gravity.

$$Y = 0.13986 + 0.56767(X_7) \qquad R = 0.7562$$

Step 2. Whole-tree specific gravity as predicted by core specific gravity and rings per inch.

$$Y = 0.14719 + 0.52984(X_7) + 0.00020(X_5) \qquad R = 0.7641$$

Step 3. Whole-tree specific gravity as predicted by core specific gravity, rings per inch and topographic site.

$$Y = 0.13873 + 0.53830(X_7) + 0.00018(X_5) + 0.00176(X_{12})$$

$$R = 0.7698$$

Step 4. Whole-tree specific gravity as predicted by core specific gravity, rings per inch, topographic site and elevation.

$$Y = 0.17978 + 0.52084(X_7) + 0.00019(X_5) + 0.00207(X_{12})$$

$$-0.000003(X_{10}) \qquad R = 0.7754$$

Where: Y = Whole-tree specific gravity.

X_5 = Rings per inch.

X_7 = Core specific gravity.

X_{10} = Elevation.

X_{12} = Topographic site.

TABLE 11.--Step-wise regression summary for the four significant variables.

Step Number	Variable Entered	Multiple R	R^2	Increases in R^2
1	Core Sp. Gr.	0.7562	0.5719	0.5719
2	R.P.I.	0.7641	0.5838	0.0119
3	Site	0.7698	0.5926	0.0088
4	Elevation	0.7754	0.6013	0.0087

variables have been omitted. This is accomplished by plotting the residuals from regression for each variable. If a trend or pattern is evident in the plotted residuals it becomes necessary to search for a transformation of that variable that would change the pattern or trend to a linear relationship. This new transformed variable would improve the prediction of the dependent variable when entered into the equation. For the four significant variables in this study the plotted residuals did not reveal any such transformation would be advantageous.

In a second multiple regression analysis, core specific gravity was omitted as one of the independent variables. This was done to evaluate the relative importance of other variables that may have been hidden by the strong correlation between core and whole-tree specific gravity. In this analysis, the four variables significantly correlated with whole-tree specific gravity at the five percent level of significance are; rings per inch, diameter breast height, elevation and

elevation x latitude. These four variables in combination account for 33.6 percent of the variance in whole-tree specific gravity. It is interesting to note that with core specific gravity omitted, site is no longer significantly related to whole-tree specific gravity while diameter breast height and elevation x latitude become important. The simple correlation coefficients and the inter-correlations for these four variables are reported on table 12. The results from this analysis support those conclusions reached earlier in this paper that a significant decrease in specific gravity can be expected with an increase in tree diameter and stand elevation. Growth rate or rings per inch produces a higher correlation with whole-tree specific gravity

TABLE 12. --Simple correlation coefficients and intercorrelations between the four significant independent variables omitting core specific gravity.

	Rings per inch	Diameter breast height	Elevation	Elevation X latitude
Whole-tree specific gravity	0.416	-0.400	-0.229	-0.114
R. P. I	1.000	-0.181	-0.012	0.066
D. B. H.		1.000	0.052	0.046
Elevation			1.000	0.849
Elevation x Lat.				1.000

in both cases of multiple regression than the earlier calculations or simple correlation-coefficient would suggest. For the benefit of comparison, Collett (14) used five basic variables plus 20 transformations to predict the whole-tree specific gravity of lodgepole pine. Of the 25 independent variables, two variables accounted for nearly all the reduction in the variance of the dependent variable or 24.5 percent. This compares with the 33.6 percent of the variation in whole-tree specific gravity accounted for in this study by using variables other than core specific gravity.

In summarizing, 60.13 percent of the variation in whole-tree specific gravity can be accounted for by four easily measured variables i.e., increment core specific gravity extracted at breast height, growth rings per inch, topographic site and elevation. Core specific gravity alone does nearly as well in accounting for 57.19 percent of the variation. The results from this multiple regression agree favorably with similar analyses reported for other species (45, 76, 88, 89 and 97).

Weighting of increment cores

The question should be considered as to the validity of an increment core representing the cross-section of a tree bole. Perhaps a wedge shaped specimen would be more representative of the cross-sectional area. Such a specimen, however, would not lend itself to

nondestructive sampling methods. Krahmer (41), while studying the specific gravity variations in western hemlock worked with strips as well as wedge shaped specimens taken in the transverse direction. He reports a significant difference between specific gravity as measured on the two specimens but suggests some of the difference might be attributed to undetected reaction wood in the larger wedge shaped specimens. For these data, figure 12 illustrates that the specific gravity of the breast height disk is a better predictor of whole-tree specific gravity than the core.

In an attempt to improve the correlation between whole-tree and increment core specific gravity in this study, the cores taken from 21 trees were segmented and the specific gravity of each segment was weighted by the relative volume of wood each represented in the trees cross-section. The procedure is outlined in Chapter III.

The mean specific gravities of the core segments along with the number of observations associated with each mean are reported in table 13.

TABLE 13.--Mean specific gravities of segmented increment cores.

	Cambium →					Pith
	segment 1	segment 2	segment 3	segment 4	segment 5	segment 6
$\bar{x}$	0.324	0.330	0.331	0.346	0.369	0.391
n	21	21	21	21	19	10

The weighted core specific gravity is 0. 336. In contrast, the unweighted mean of the 21 cores is 0. 346 while the mean whole-tree specific gravity of the same trees is 0. 338. Through weighting we have reduced the difference between the means from 0. 008 to 0. 002. The student's t test indicates no significance between the whole-tree specific gravity and the weighted core specific gravity of the 21 trees at the one percent level of significance. In projecting this difference to the means for the 316 trees, we find the grand mean of the core specific gravity reduced from 0. 342 to 0. 332. Since the grand mean of the whole-tree specific gravity is 0. 334 the original difference of 0. 008 has been reduced to 0. 002, identical to the difference for the 21 trees. However, the comparison of the means alone is not adequate. To assure an improvement by weighting increment cores it is necessary to look at the correlation between whole-tree and weighted core specific gravities. Using data from the 21 trees, a simple linear regression between whole-tree and increment core (unweighted) specific gravities produces a coefficient of determination of 0. 1864. The same analysis using weighted increment core specific gravity produced a coefficient of determination of 0. 3480. Therefore, by weighting the increment cores an additional 16. 36 percent of the variation in whole-tree specific gravity is accounted for or nearly a two fold improvement. It is interesting to note that the coefficient of determination for the 21 trees (whole-tree specific gravity with

unweighted cores) is considerably lower than the comparable figure of 0.5544 for all 316 sample trees. Perhaps one can only conclude that these data produce promising results for improving the predictability of whole-tree specific gravity with increment cores.

Another interesting relationship borne out by the segmenting of increment cores is that specific gravity tends to decrease from the pith to the cambium. For most conifers the reverse is true. Krahmer (41) reports, however, a similar trend for western hemlock. He found the maximum specific gravity at the pith with a rapid decrease for a short distance from the pith. Beyond this zone, there was no evidence of a continuous increase or decrease. Wellwood and Jurazs (95) report a similar trend for western redcedar with the exception that for this species there was a slight increase after approximately the first 100 years of growth. The specific gravity data on the segmented cores indicate a regression trend exists. A simple linear regression analysis was computed as graphically illustrated in figure 24. In table 14 the data is presented for testing that the slope of this line is significantly different from zero. There is a significant difference at all levels.

Although the extent of this investigation is limited to 21 of 316 sample trees, the results indicate some interesting relationships. One important limitation in the weighting method used for the core segments is that trees are normally eccentric rather than having

Figure 24. ---Regression line of increment core specific gravity in the transverse direction.

$r^2 = 0.2768$

$Y = 0.30742 + 0.01220\ X$

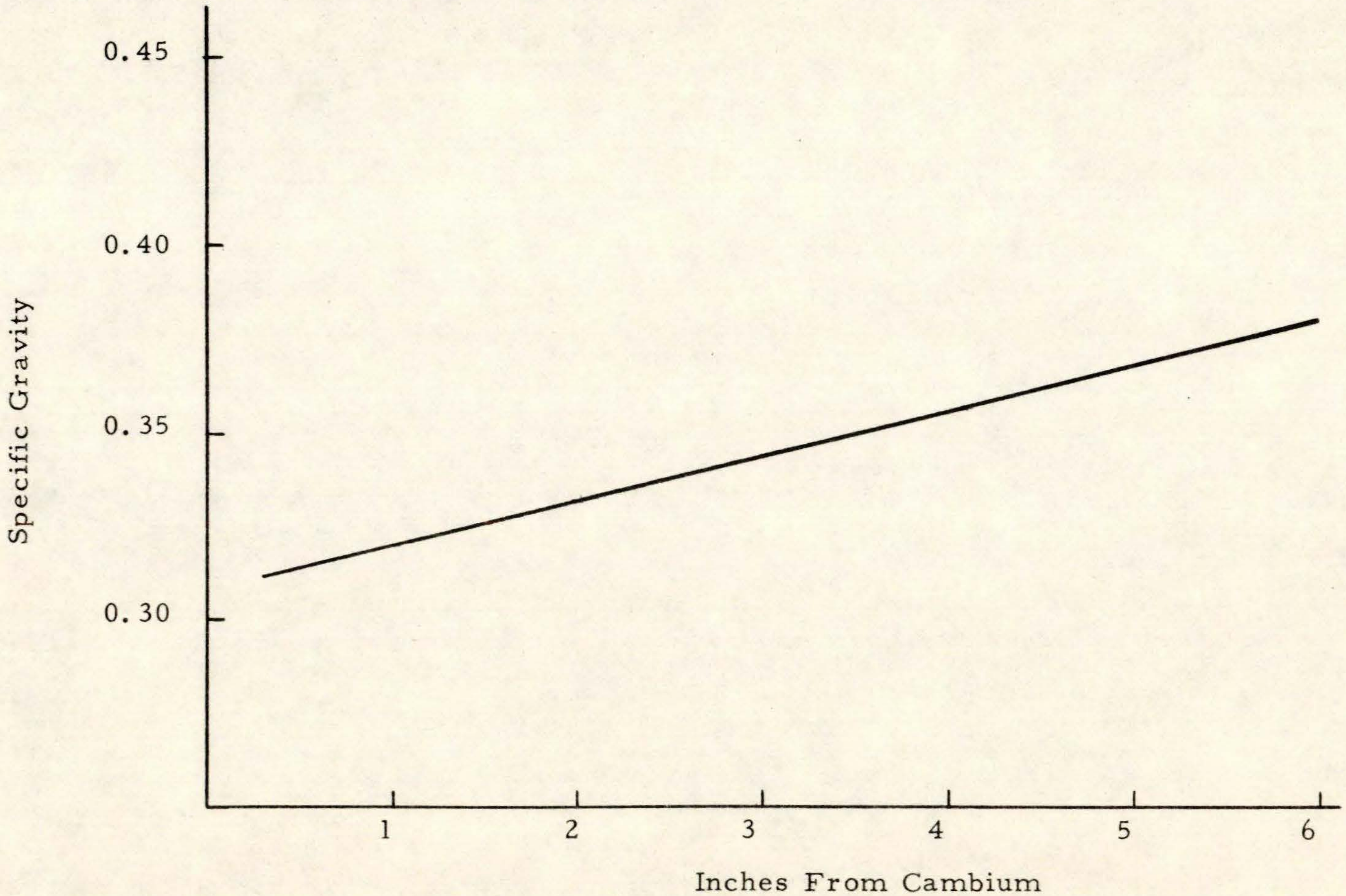


TABLE 14. --Analysis of variance summary for testing the significance of the regression between increment core segment specific gravity and distance along the cross-sectional radius (figure 24).

Source	D.F.	S.S.	M.S.	F.
Total	112	0.153872		
Regression	1	0.042585	0.042585	42.5**
Residual	111	0.111287	0.001003	

the pith in the geometric center. Therefore, the length of the increment cores was governed by where along the trees circumference the core was extracted. In this experiment the cores ranged in length from 4.713 to 6.619 which resulted in only 10 observations in the sixth inch zone or the one nearest the pith. This introduced error into the weighted average. The problem of equal proportions of the core representing unequal proportions of the cross-section was discussed in the Western Wood Density Survey report (97) issued by the U.S. Forest Products Laboratory in 1965. In that study the core length was limited to 10 inches in length. Therefore, in large trees the low density wood near the pith was not represented by the core. Thus, the greater proportion of the wood in larger trees was more proportionately sampled, however the cores apparently extended to the pith on those trees having a radius less than 10 inches. In this

study only 46 trees were sampled having diameters greater than 20 inches at breast height.

The effect of extractives on specific gravity

Although extractives are a major constituent of wood they are not a part of the woods structure. Extractives tend to mask the relationship of specific gravity and strength, contributing nothing to strength while appreciatively increasing specific gravity. In some instances they have desirable affects on such properties as color, odor, taste and resistance to decay. The contribution of extractives to wood specific gravity varies considerably by species. Extraneous materials may be present in very small quantities or they may constitute more than 20 percent of the ovendry weight. Engelmann spruce is considered to be an extractive free wood. Since the wood of any species contains some extractives the statement only serves to illustrate the relationship of spruce to more highly resinous species. The results of extraction of 18 sapwood specimens and 17 heartwood specimens are reported in table 15. The volume of each specimen was measured before and after extraction as indicated under procedures, Chapter III. There was a general tendency for the volumes to increase after extraction. This is believed to be due to a swelling effect. Provided the extractives had occupied hydrogen bonds, they then became available to hydroxyl groups after extraction. This could have taken place since the last phase of the extraction was done

with water. Because of this swelling, the specific gravity values based on the specimens original volume are most realistic. As reported in table 15, the removal of extractives in the sapwood specimens resulted in a 3.52 percent decrease in specific gravity while the heartwood reduction was 3.10 percent. The student's t test indicates the difference between the two is significant at the one percent level. Since it is normal to expect a greater amount of extractives in the heartwood the reverse is difficult to explain. To assure that all extractives were removed, the specimens were ground in a Wiley mill as described in Chapter III and extracted a second time. The extraction of the ground wood produced a 0.51 percent reduction in the ovendry weight of the heartwood specimens and a 0.22 percent reduction in ovendry weight of the sapwood.

TABLE 15.--Summary of the specific gravity of Engelmann spruce wood before and after extraction.

EXTRACTION DATA

	A. Sapwood Before Extraction	B. Sapwood After Extraction	C.[1] Sapwood After Extraction	D. Heartwood Before Extraction	E. Heartwood After Extraction	F.[1] Heartwood After Extraction
ΣX	5.574	5.288	5.378	5.304	5.091	5.137
N	18	18	18	17	17	17
$\bar{X}$	0.3097	0.2938	0.2988	0.3120	0.2995	0.3022
ΣX^2	1.7288	1.5558	1.6092	1.6651	1.5353	1.5618
% CHANGE		5.1	3.52		4.0	3.14

PAIRED t TEST (one-way) SIGNIFICANT AT THE 1% LEVEL

A, B   A, C   D, E   D, F

t TEST BETWEEN MEANS C AND F SIGNIFICANT AT THE 1% LEVEL

1 Based on specimen volume before extraction

CHAPTER VI

SUMMARY AND CONCLUSIONS

Specimens for measuring the specific gravity of Engelmann spruce were collected from 316 trees growing in 13 national forests of Colorado and Wyoming. The statistical population from which the trees were sampled proportionately is; all the living merchantible Engelmann spruce trees, of average form, good vigor, without decay, excessive branchiness or lean, between 5.0 and 30.9 inches in diameter at breast height growing in Colorado and Wyoming. From each tree sampled, cross-sectional specimens were taken at breast height and at ten foot intervals thereafter, until a five inch diameter top was reached. The specific gravity (green volume, ovendry weight) of each of the 1720 cross-sections collected, was determined and then weighted by the volume of wood each represented in the tree. In addition, an increment core (0.212 inches diameter) was extracted at breast height from each tree. The specific gravity of each core was measured and then correlated with that of the whole-tree. The whole-tree specific gravity was calculated by a summation of the weighted cross-sectional values. The relationship of several easily measured variables with whole-tree specific gravity was studied using the step-wise multiple linear regression technique. Five of the

variables were measures of the tree, two were measures of the stand, four were measures of location while the remainder were combinations or transformations of the above.

The computed average whole-tree specific gravity of Engelmann spruce wood is 0. 334. This is an improvement of 0. 014 over the presently accepted value. The mean specific gravity of the 316 increment cores taken is 0. 342 which is significantly different from the average whole-tree value. The mean value of the breast height cross-section was not found to be significantly different from that of the whole tree. Simple linear regression between core specific gravity (independent variable) and that of the whole-tree (dependent variable) yielded a coefficient of determination of 0. 5544. The same analysis using the breast height value (independent variable) produced an improved coefficient of determination of 0. 7962 while a coefficient of 0. 6538 resulted from using the average of the breast height and 14. 5 foot level specimen specific gravity. The best point of sampling for specific gravity specimens is at breast height. Although the core specific gravity is not the most highly correlated with that of the tree it is the only one of the above three variables that lends itself to nondestructive sampling techniques. The correlation between core and tree specific gravity can be substantially improved by segmenting the core and weighting each segment by the relative volume of wood each represents in the trees cross-section.

Eighteen independent variables were used with the stepwise multiple linear regression technique to study their affects on whole-tree specific gravity. Only four of the variables (core specific gravity, rings per inch, topographic site and elevation) were significantly related at the one percent level. While these four variables in combination account for 60.13 percent of the variation in whole-tree specific gravity, core specific gravity alone accounts for 57.19 percent using data from 264 trees. From a practical standpoint then, of the variables tested, core specific gravity alone adequately predicts tree specific gravity. In other research (98), as much as one-third the total whole-tree specific gravity variation is suggested as being due to genetic factors.

The causes of specific gravity differences both within and between Engelmann spruce trees, as developed from this study can be summarized as follows:

a. In the vertical direction, specific gravity is highest at the base of the tree, decreases for the first 25 feet at which point it steadily increases for the next 40 feet. Above the 75 foot level specific gravity tends to decrease.

b. Whole-tree specific gravity decreases with an increase in tree diameter.

c. In the transverse direction, specific gravity is maximum at the pith with a substantial and steady decrease outward.

d. Whole-tree specific gravity increases with tree age at breast height although the relationship is not strong.

e. Rate of growth or rings per inch follows quite closely the same pattern as diameter when plotted against specific gravity, i.e., whole-tree specific gravity decreases with a decrease in the number of rings per inch.

f. Whole-tree specific gravity decreases with an increase in elevation. Regression suggests a reduction of 0.008 per 1000 feet rise in elevation.

g. Whole-tree specific gravity increases with an increase in latitude. Regression suggests an increase of 0.003 per degree.

h. Whole-tree specific gravity is lower in dominant trees verses codominant trees. There also exists a slower growth rate in the codominant trees.

i. Alcohol and benzene soluble extractives contribute approximately three percent to the specific gravity of Engelmann spruce wood.

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APPENDICES

APPENDIX TABLE OF CONTENTS

APPENDIX A

APPENDIX A.1--Wood density plot location and number of trees cut by forests.

FOREST	VOLUME IN M.B.F.	PERCENT VOLUME	FOREST INVENTORY PLOT NO.	CUTTING PLOT NO.	DEGREES LATITUDE	DEGREES LONGITUDE	NO. OF TREES
COLORADO							
Arapaho	1857	8.2	55	1-2	39.75	106.08	7
			71	3-4	39.80	106.00	6
			72	5-6	39.80	106.00	6
			148	7-8	39.92	105.92	6
Gunnison	2649	11.7	71	25-26	38.53	107.42	6
			118	27-28	38.03	107.15	6
			134	29-30	39.00	107.67	8
			152	31-32	38.87	106.65	7
			128	33-34	39.03	107.67	8
Pike	880	3.9	21	39-40	39.33	106.08	6
			36	41-42	39.55	105.70	6
Rio Grande	3743	16.4	49	61-62	37.78	107.53	6
			82	63-64	37.83	106.72	7
			117	65-66	37.67	107.00	6
			123	67-68	37.70	107.05	6
			138	69-70	37.40	106.08	8
			170	71-72	37.47	106.67	8
			171	73-74	37.42	106.67	8
Roosevelt	558	2.6	24	35-36	40.83	105.67	8
			145	37-38	40.58	105.67	8
Routt	1557	6.9	1	43-44	40.80	107.25	5
			21	45-46	40.80	107.33	9
			99	47-48	40.57	106.67	7
San Isabel	748	3.3	129	49-50	38.63	106.35	6
			35	51-52	38.80	106.37	4
San Juan	4.936	21.7	68	9-10	37.63	107.95	8
			13	11-12	37.78	108.07	9
			50	13-14	37.62	108.17	8
			67	15-16	37.72	107.97	8
			74	17-18	37.72	107.92	8
			87	19-20	31.55	107.70	7
			163	21, 22, -91	37.50	107.30	12
			194	23	37.37	106.70	4
Uncompahgre	1489	6.6	164	85-86	37.87	107.92	6
			80	87-88	38.37	108.18	8
			42	89-90	39.05	107.95	6
White River	1929	8.5	147	53-54	39.58	106.33	6
			146	55-56	39.70	106.35	6
			208	57-58	39.33	106.58	8
			120	92-93	39.53	106.58	8
			254	59-60	39.12	106.83	8
WYOMING							
Bighorn	704	3.1	178	75-76	44.20	107.03	5
Medicine Bow	896	4.0	46	81-82	41.33	106.32	6
			139	83-84	41.18	106.97	6
Shoshone	1.97	3.1	50A	77	44.66	109.37	6
			136	79-80	43.63	109.92	5
TOTALS	22673	100	46	91			316

APPENDIX A.2--Sample trees by forest and diameter class.

	Diameter Classes													
Forest	5-6.9	7-8.9	9-10.9	11-12.9	13-14.9	15-16.9	17-18.9	19-20.9	21-22.9	23-24.9	25-26.9	27-28.9	29-30.9	Totals
Arapaho		2	6	9	2	4	1			1				25
Gunnison	1	5	7	8	6	7						1		35
Pike	1	1	1	4	1	2	2							12
Rio Grande	6	4	7	15	9	6	1		1					49
Roosevelt	2	2	9		2				1					16
Routt	4	2			1	4	6	1			1	1	1	21
San Isabel				5	4	1								10
San Juan	2	8	3		5	5	11	8	8	8	4	1	1	64
Uncompahgre		4	7	2			3	3		1				20
White River		1	8	5	6	8	3	2	3					36
Bighorn	1						2	2						5
Medicine Bow		1	6		4		1							12
Shoshone	2	2	2					5						11
TOTALS	19	32	56	48	40	37	30	21	13	10	5	3	2	316

APPENDIX B

APPENDIX B.1-- Analysis of variance summary table for testing specific gravity differences between forests.

Source	D. F.	S. S.	M. S.	F.
Total	315	0.1906	0.0018	3.212
Treatment	12	0.0215	0.0006	
Residual	303	0.1691		

APPENDIX B.2 - Data Averages by national forests.

	Forest												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Number of trees	25	35	12	49	16	21	10	64	20	36	5	12	11
Whole tree sp. gr.	.337	.338	.333	.331	.359	.340	.331	.323	.332	.333	.335	.331	.346
Core sp. gr.	.340	.349	.338	.340	.377	.359	.356	.323	.349	.331	.341	.352	.356
Rings per inch	22.2	25.5	39.6	31.2	57.0	30.4	23.3	21.5	17.2	21.4	32.2	43.8	23.9
Age (years at BH)	124	144	208	152	251	203	134	154	101	138	225	211	130
Total height (ft.)	71.7	71.6	52.7	63.4	50.4	75.6	64.4	90.9	73.3	71.9	61.4	44.6	61.7
Sp. gr. at 4.5 ft.	.338	.340	.338	.337	.367	.346	.337	.323	.336	.333	.336	.332	.353
" 14.5 ft.	.332	.335	.328	.326	.362	.338	.329	.320	.326	.329	.326	.326	.336
" 24.5 ft.	.333	.337	.331	.323	.351	.327	.324	.319	.329	.331	.320	.337	.339
" 34.5 ft.	.340	.343	.336	.325	.354	.328	.331	.315	.328	.334	.337	.332	.376
" 44.5 ft.	.342	.338	.343	.326	.359	.338	.332	.325	.334	.340	.362	.357	.348
" 54.5 ft.	.360	.343	.342	.321	.371	.341	.349	.337	.326	.346	.378		.364
" 64.5 ft.	.351	.343		.346	.447	.343	.372	.333	.350	.351			.350
" 74.5 ft.	.336	.365		.332	.438	.351		.342	.356	.356			.373
" 84.5 ft.	.354					.349		.339	.319	.332			
" 94.5 ft.						.356		.348	.351				

Forest Codes

1 Arapaho
2 Gunnison
3 Pike
4 Rio Grande
5 Roosevelt
6 Routt
7 San Isabel
8 San Juan
9 Uncompahgre
10 White River
11 Bighorn
12 Medicine Bow
13 Shoshone

APPENDIX B.3-- Variable means by crown classes.

	Dominant	Codominant
number of trees	121	192
Whole-tree specific gravity	0.325	0.339
Core specific gravity	0.327	0.351
Rings per inch	24.5	29.3
Age (years at b.h.)	182	141
Total tree height	85.6	62.1
Length of live crown	58.5	40.0
Height to Merchantible Top	70.2	46.7

note: Differences are all significant at the one percent level.

APPENDIX C

APPENDIX C.1-- List of variables and their codes as used in the step-wise multiple regression analysis.

	X
Basal Area	1
Diameter Breast Height	2
Total Tree Height	3
Age	4
Rings Per Inch	5
Whole-tree Specific Gravity	6
Core Specific Gravity	7
Latitude	8
Longitude	9
Elevation	10
Slope Aspect	11
Topographic Site	12
Transformations	
8 X 10	13
2 X 3	14
2 squared	15
4 X 1	16
Reciprocal of 4	17
2 divided by 4	18
10 squared divided by 4	19

APPENDIX C.2--Correlation matrix from the step-wise multiple regression.

Variable Code	1	2	3	4	5	6	7	8	9
1	1.000	0.067	0.059	0.279	0.180	0.063	0.053	-.114	0.075
2		1.000	0.534	0.467	-.181	-.400	-.495	-.019	0.176
3			1.000	0.098	-.283	-.234	-.266	-.136	0.275
4				1.000	0.712	0.086	0.001	0.133	-.165
5					1.000	0.416	0.419	0.133	-.248
6 = y						1.000	0.756	0.233	-.097
7							1.000	0.227	-.094
8								1.000	-.181
9									1.000

Variable Code	10	11	12	13	14	15	16	17	18	19
1	0.100	0.081	0.041	0.051	0.070	0.071	0.670	-.214	-.229	-.187
2	0.052	-.032	-.025	0.046	0.922	0.980	0.387	-.452	0.169	-.424
3	-.087	0.001	-.029	-.174	0.782	0.513	0.119	-.138	0.202	-.152
4	0.074	0.021	0.089	0.162	0.350	0.455	0.846	-.874	-.683	-.834
5	-.012	-.009	0.066	0.066	-.242	-.162	0.566	-.637	-.796	-.622
6	-.229	0.035	0.051	-.114	-.354	-.369	0.073	-.065	-.327	-.109
7	-.219	0.041	-.070	-.109	-.430	-.455	0.013	0.002	-.321	-.049
8	-.444	0.004	-.025	0.093	-.065	-.001	0.041	-.017	-.089	-.113
9	-.266	0.114	-.285	-.427	0.274	0.207	-.100	0.131	0.211	0.050
10	1.000	-.091	0.192	0.849	-.056	0.026	0.095	-.043	-.011	0.193
11		1.000	0.074	-.104	-.044	-.066	0.096	-.085	-.116	-.106
12			1.000	0.209	-.034	-.027	0.173	0.013	-.025	0.076
13				1.000	-.099	0.027	0.134	-.056	-.062	0.151
14					1.000	0.924	0.315	-.360	0.202	-.360
15						1.000	0.391	-.427	0.149	-.408
16							1.000	-.693	-.563	-.655
17								1.000	0.753	0.965
18									1.000	0.744
19										1.000

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